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EFFECT OF FILM THICKNESS,
VOIDS AND PERMEABILITY ON
ASPHALT HARDENING IN
ASPHALT MIXTURES

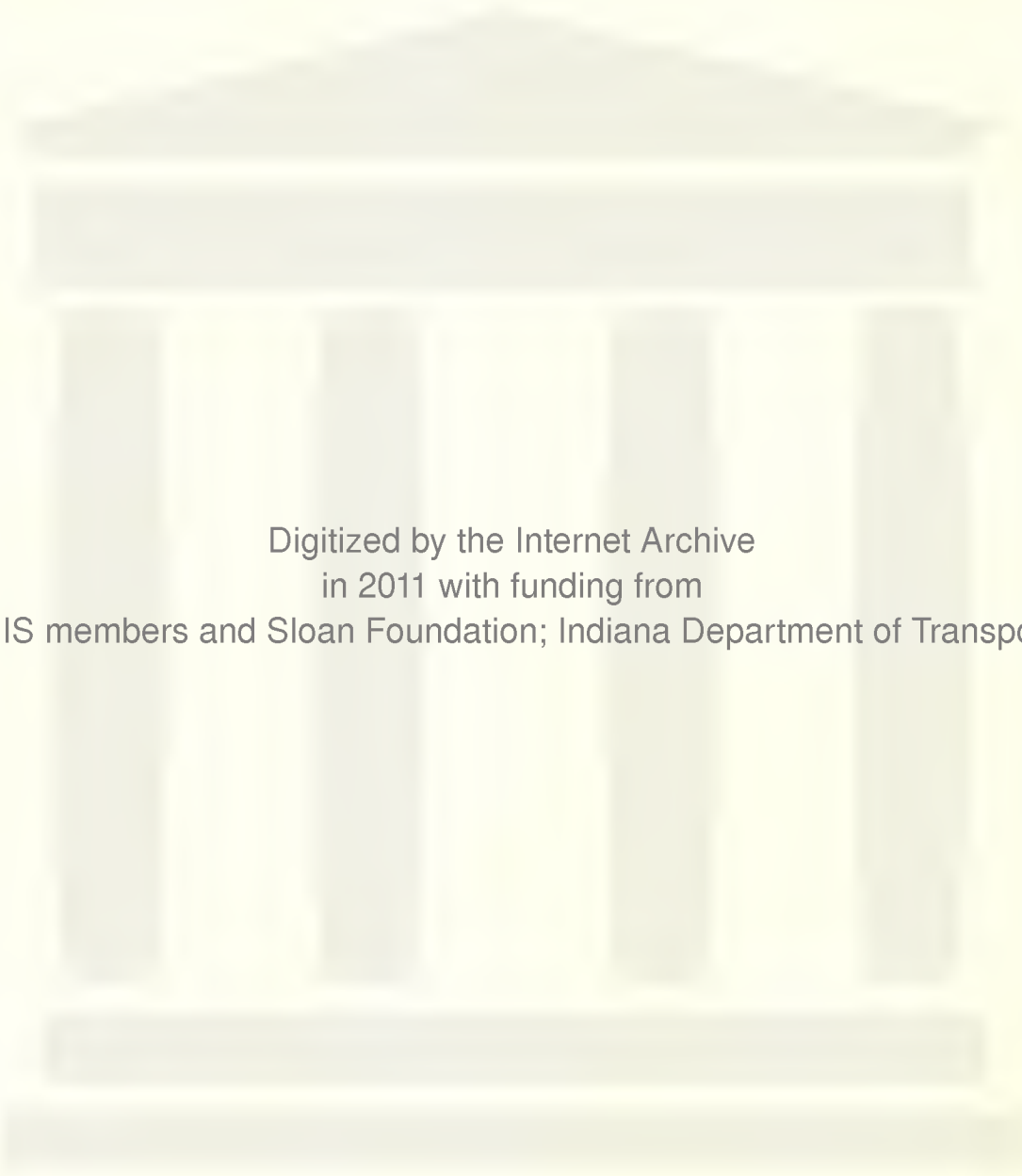
Arun Kumar



EFFECT OF FILM THICKNESS, VOIDS AND PERMEABILITY ON
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Final Report

EFFECT OF FILM THICKNESS, VOIDS AND PERMEABILITY ON
ASPHALT HARDENING IN ASPHALT MIXTURES

by

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ABSTRACT

Kumar, Arun. Ph.D., Purdue University, August 1976. Effect of Film Thickness, Voids and Permeability on Asphalt Hardening in Asphalt Mixtures. Major Professor: Prof. William H. Goetz.

Laboratory experiments were conducted on asphaltic mixtures to study the effect of asphalt film thickness, voids and permeability on asphalt hardening.

Limestone aggregate and a 200-250 penetration grade asphalt were used in the study. Specimens of both single-size and graded mixtures were prepared using gyratory compaction. The specimens were then subjected to permeability measurements followed by alternate cycles of accelerated oxidation and creep testing. After the oxidation and testing cycles, percent accessible void measurements were made for each specimen. The accessible voids were measured using four different techniques; 24-hour soaking, hand pumping, under vacuum (absolute pressure 10 cm. mercury) and under vacuum (absolute pressure 2.5 cm. mercury). Finally, the asphalt was recovered from each specimen and its penetration determined. Before asphalt recovery, however, each specimen was subjected to a final creep test.

The results, based on statistical analysis, indicated that for single-size mixtures the ratio of film thickness factor to permeability is the best predictor of mixture's resistance to hardening caused by

accelerated oxidation. For graded mixtures, the asphalt film thickness concept breaks down and permeability alone was found to be the best predictor of a mixture's resistance to hardening.

The results show that permeability is related to the entire void system of graded asphaltic mixtures. Straight line relationships were observed between the log of permeability and voids. Since permeability was found to be closely related to the accessible air voids (hand pumping), the measurement of percent accessible air voids (hand pumping) can be substituted for permeability as a predictor of mixture resistance to hardening in graded mixtures.

A comparison between the penetration test results of the recovered asphalt from asphaltic mixtures and their corresponding creep test results indicates that the creep test may be used as a measure of asphalt hardening. Therefore, this test can be employed as a non-destructive test to measure progressive asphalt hardening in asphaltic mixtures. The devised durability test was evaluated and was found to be a good laboratory procedure for evaluation of asphalt hardening in asphaltic mixtures.

INTRODUCTION

The design of asphalt paving mixtures for highway pavements generally requires a balance of various desirable mixture properties. Durability is one of them. A mixture is said to be durable when it offers long term resistance to weathering (aging) and gives good performance without abnormal ravelling and cracking of the paving surface.

For the mixture to be durable it is essential that one of its constituents, asphalt cement, should also be durable. Vallerger, Monismith and Grantham (1) state that disintegration and fracture are the two types of pavement distress that result from a non-durable asphalt. Further, they mention that hardening of asphalt is of critical importance with respect to disintegration and fracture. This indicates that durability of asphalt cement can be measured by its ability to withstand hardening and loss in flexibility with time (2, 3).

The durability of bituminous mixtures cannot, logically, be discussed in terms of individual components because a durable asphalt and a durable aggregate do not necessarily insure a durable mixture (4, 5). Aside from the matter of compatibility, the asphalt in mixtures composed of the same ingredients may not be exposed in the same manner. Such mixtures can be prepared by mixing the two constituents in varying proportions and then compacting them with

various compactive efforts. This will produce mixtures with variable percent total air voids, percent accessible air voids, voids in the mineral aggregate, asphalt film thickness, density, and permeability of the compacted mixture.

There is a general belief that a dense-graded mixture is desirable from the durability point of view. Finn writes (6):

"To minimize the effects of weathering, experience would indicate that high asphalt contents, dense gradation of aggregate and a well compacted impervious mixture is required."

The work done by McLaughlin and Goetz (7) indicates that a dense-graded mixture is not necessarily the most durable. They write:

"A dense-graded mixture is not necessarily the best from a durability stand point. The factor of asphalt film thickness must be considered."

Logically speaking, only that asphalt in a compacted asphaltic mixture which is accessible to open air will harden by oxidation. If the thickness of the asphalt coating on the aggregate is greater, a longer time will be needed for the entire thickness of the asphalt film to become hardened and vice versa.

Based on the above reasoning it seemed useful to undertake a laboratory study to examine the influence of asphalt film thickness, voids and permeability on asphalt hardening in asphalt mixtures. Accordingly, some graded mixtures used in Indiana and some single-size mixtures were selected for the study. The permeability, voids and asphalt film thickness values were obtained for the compacted specimens. The specimens were subjected to accelerated oxidation.

The hardening of asphalt in the asphaltic mixture has been measured in the past by means of destructive testing. This is achieved

by extracting asphalt from the mixture and then carrying out tests such as penetration, viscosity, etc., on the recovered asphalt. In this study, a non-destructive compressive creep test was used on the asphaltic mixture. It was contemplated that the creep response of the mixture would give an indication of the amount of asphalt hardening.

REVIEW OF LITERATURE

Attempts have been made in the past to study the influence of various mixture variables such as, voids, permeability, film thickness, etc. on the asphalt mixture durability.

McLaughlin and Goetz (7) were among the first (1955) to hypothesize that permeability is a better measure of durability as compared to void content alone. Permeability, in their opinion, is a measure of the capacity of the porous medium to transmit fluid whereas the usual calculation of voids in a bituminous mixture does not provide any direct measure of the forces producing disintegration. They varied asphalt content and aggregate gradation of the asphalt mixture and prepared specimens at varying compactive efforts. Permeability and void content values of the compacted mixture were determined. A linear relationship was obtained between percent air voids and log permeability (cm^2). No relationship between permeability and durability, as measured by percent loss in sonic modulus caused by laboratory freezing and thawing, was observed.

Heithaus and Johnson (8) showed (1958) that asphalt hardening increases with increase in initial void content. In their opinion, the increase in rate of hardening is due to increase in air permeability which they assumed to be a function of voids. However, no permeability measurements were made.

At the 1958 annual meeting of the Association of Asphalt Paving Technologists a symposium was held on the hardening of paving asphalts (9). There it was pointed out that asphalt film thickness is important because it affects durability. The following year, Campen, et al. presented a paper (10) dealing with the relationships between voids, surface area, film thickness and stability of bituminous mixtures. They summarized some of their conclusions as follows:

"The minimum voids in the aggregate do not indicate the surface area of the aggregate. In fact, aggregates may have like voids but the surface area of one may be twice that of the other.

The surface area of the aggregate does not indicate the asphalt content required to produce minimum aggregate voids. In general, the asphalt requirement increases as the surface area increases, but at much slower rate than that demanded by the direct proportionality."

These authors also established minimum and maximum values of film thickness for satisfactory pavement performance.

Hein and Schmidt (11) performed a study on air permeability of asphalt concrete and suggested (1961) that permeability measurements should be an essential part of routine mix design studies. Their results indicate that void contents of mixes are not necessarily proportional to permeability when the variation is by mix gradation. Further they state that increase in the fines can decrease permeability while still retaining mix stability.

Warner and Moavenzadeh (12), in 1964, conducted a study on permeability and compaction characteristics of bituminous mixtures and showed the effects of asphalt content and aggregate gradation on the void-permeability relationship.

Goode and Lufsey (13) were among the first (1965) to perform a study on voids, permeability and film thickness vs. asphalt hardening.

They write:

"A pavement of high air permeability might be expected to show early evidence of distress resulting from rapid hardening of the asphalt; but high permeability could be the result of insufficient asphalt in the mixture or inadequate compaction with an accompanying high percentage of air voids; or the use of an aggregate gradation of excessively high surface and with an accompanying thin film of asphalt coating on the aggregate particles."

Based on their study they concluded that when aggregate gradation is a variable, none of the single factors; air voids, air permeability, or bituminous film thickness can be satisfactorily related to the quality of a mixture with respect to resistance to asphalt hardening. Their study indicated that a combined factor consisting of the ratio of air voids to bitumen index provided a satisfactory means of comparing mixtures in the above respect, regardless of aggregate gradation. They did not find the importance of air permeability in the above combined factor. In other words, air permeability or air void content, per se, did not appear to be factors affecting the rate of asphalt hardening.

These authors prepared specimens by means of a gyratory compactor. They varied aggregate gradation and asphalt film thickness but kept compactive effort constant. From their data it appears that differences in permeability values between prepared specimens having the same asphalt content and variable aggregate gradation is rather small. This may be due to the fact that variations in gradation were minor.

In 1969, Smith and Gotolski (14) presented the results of their investigation which was conducted to evaluate the effects of air permeance and air void content on the durability of asphaltic concrete as measured by asphalt hardening. Some of their conclusions were:

"Asphalt hardening as measured by changes in penetration and changes in percent asphaltenes is dependent on the portion of the total void content that is accessible to air."

and

"Air permeability is a good indicator of the extent, of the accessible air void system."

Based on a field study, Vallergera and Halstead (15) concluded (1971) that, above two percent total air voids, the rate of asphalt hardening increases with increasing air voids. Gotolski and Roberts (16) write in their report (1973) that:

"The level of air voids in a pavement appears to be a major factor influencing the rate of pavement hardening. No permeability measurements were made."

The above review of literature indicates that permeability is an important factor that determines the durability of a bituminous mixture. Little emphasis has been placed so far on the role of film thickness on asphalt hardening in asphalt mixtures. Goode and Lufsey (13) used bitumen index as an expression of bituminous film thickness and showed that this factor in combination with other factors influences asphalt hardening.

Other factors being equal, it was postulated that only two factors, permeability and asphalt film thickness, control the durability of an open-graded compacted asphaltic mixture.

MATERIALS AND SPECIMEN PREPARATION

In this section, the materials used for this investigation and their source and properties are presented, the selected aggregate gradations are given, and the procedure used for specimen preparation is described. The presentation is in the following order: Aggregate, Asphalt, Mixture Variables, Specimen Preparation.

Aggregate

Limestone aggregate, commonly used by the Indiana State Highway Commission (17) in their hot asphaltic concrete surface mixtures, was used in the study. It was obtained from Napoleon, Indiana.

The aggregate was first oven dried and then sieved for each sieve size fraction from 3/4 inch down to passing U.S. sieve size number 100. Each sieve size fraction of the aggregate was then washed, dried to constant weight and stored in a 15 gallon container in the laboratory. Specific gravity, water absorption, asphalt absorption and centrifuge kerosene equivalent tests were conducted on each aggregate fraction. The first two tests were according to ASTM methods C 127 and C 128. Asphalt absorption was obtained using a vacuum pycnometer (18). The CKE test was carried out in accordance with the transportation laboratory procedure of the State of California (19) with an exception that kerosene was used for both coarse and fine aggregates. The results of these tests are shown in Tables 1A and 1B.

Table 1A. Results of Specific Gravity and Absorption Tests on Aggregates

U.S. Sieve Size	Bulk Sp. Gr.	Bulk Sp. Gr. (SSD Basis)	Apparent Sp. Gr.	Water Absorption Percent	Asphalt Absorption Percent
3/4 in - 1/2 in	2.671	2.692	2.729	0.791	0.408
1/2 in - 3/8 in	2.663	2.686	2.727	0.896	0.525
3/8 in - #4	2.654	2.680	2.726	1.016	0.562
#4 - #8	2.640	2.674	2.731	1.256	0.588
#8 - #16	2.637	2.671	2.732	1.317	0.691
#16 - #30	2.634	2.670	2.730	1.358	0.743
#30 - #50	2.628	2.667	2.733	1.399	0.805
#50 - #100	2.622	2.661		1.522	0.866

Table 1B. Results of Surface Area Tests on Aggregates

U.S. Sieve Size	Surface Area Based on			
	CKE Test		Surface Area Factor	
	Amount of Kerosene Retained, %	Ratio to Sieve Size 3/4 in-1/2 in	Ratio to Sieve Size #4-#8	Surface Area, sq. ft. per lb.
3/4 in - 1/2 in	0.11	1.0		
1/2 in - 3/8 in	0.15	1.4		
3/8 in - #4	0.29	2.6		
#4 - #8	0.47	4.3	1.0	4
#8 - #16	0.8	7.3	1.7	8
#16 - #30	1.3	11.8	2.8	14
#30 - #50	2.6	23.6	5.5	30
#50 - #100	4.0	36.4	8.5	60
				15.0

Asphalt

For the purposes of this study, it was desirable to use a soft grade of asphalt as the degree of hardening would then be more pronounced. A 200-250 penetration grade asphalt was selected. It was obtained from the Asphalt Materials Company, Indianapolis, Indiana. Table 2 presents the results of the tests on this asphalt.

Aggregate Gradation

In this investigation, both single-size and graded mixtures were used.

The term 'single-size mixture' in this report means a combination of two sieve-size fractions of aggregate. Such combinations for various specimens (nos. S1 to S6) are given in Figure 1 and Table 3.

For graded mixtures, two surface mixture gradations, Type A no. 9 and Type B no. 11 used by the Indiana State Highway Commission (17), were selected. These conformed to specifications except that no aggregate fraction passing sieve size no. 100 was used. The gradations used for various specimens (nos. G1 to G4, C1 to C6 and A1 to A6) are presented in Figure 2 and Table 4.

Specimen Preparation

The aggregates were batched for each specimen by component fractions in accordance with the cumulative batch weight formula (based on the selected aggregate gradation). This was accomplished by weighing the cold dried aggregates on a Toledo Scale sensitive to one gram. The batch weight for each specimen is given in Tables 5 to 8.

Table 2. Results of Tests on Asphalt Cement

		Test Method
Solubility in Carbon Tetrachloride, %	99.54	ASTM D2042
Penetration, 100 grams, 5 sec., 77F (25C)	222	ASTM D5
Loss on Heating, 50 grams, 5 hr., 325F (163C), %	0.063	ASTM D1754
Penetration of Residue, % of Original	47	ASTM D5
Specific Gravity at 77F (25C)	1.018	ASTM D70
Flash Point, Cleveland Open Cup, °F	350 ⁺	ASTM D92
Ductility at 77F (25C), 5 cm/min., cm	100 ⁺	ASTM D113
Kinematic Viscosity at 275F (135C), cSt	129.8	ASTM D2170
Absolute Viscosity at 140F (60C), poises	290.0	ASTM D2171
Spot Test, Standard Naphtha	Negative	AASHTO T 102

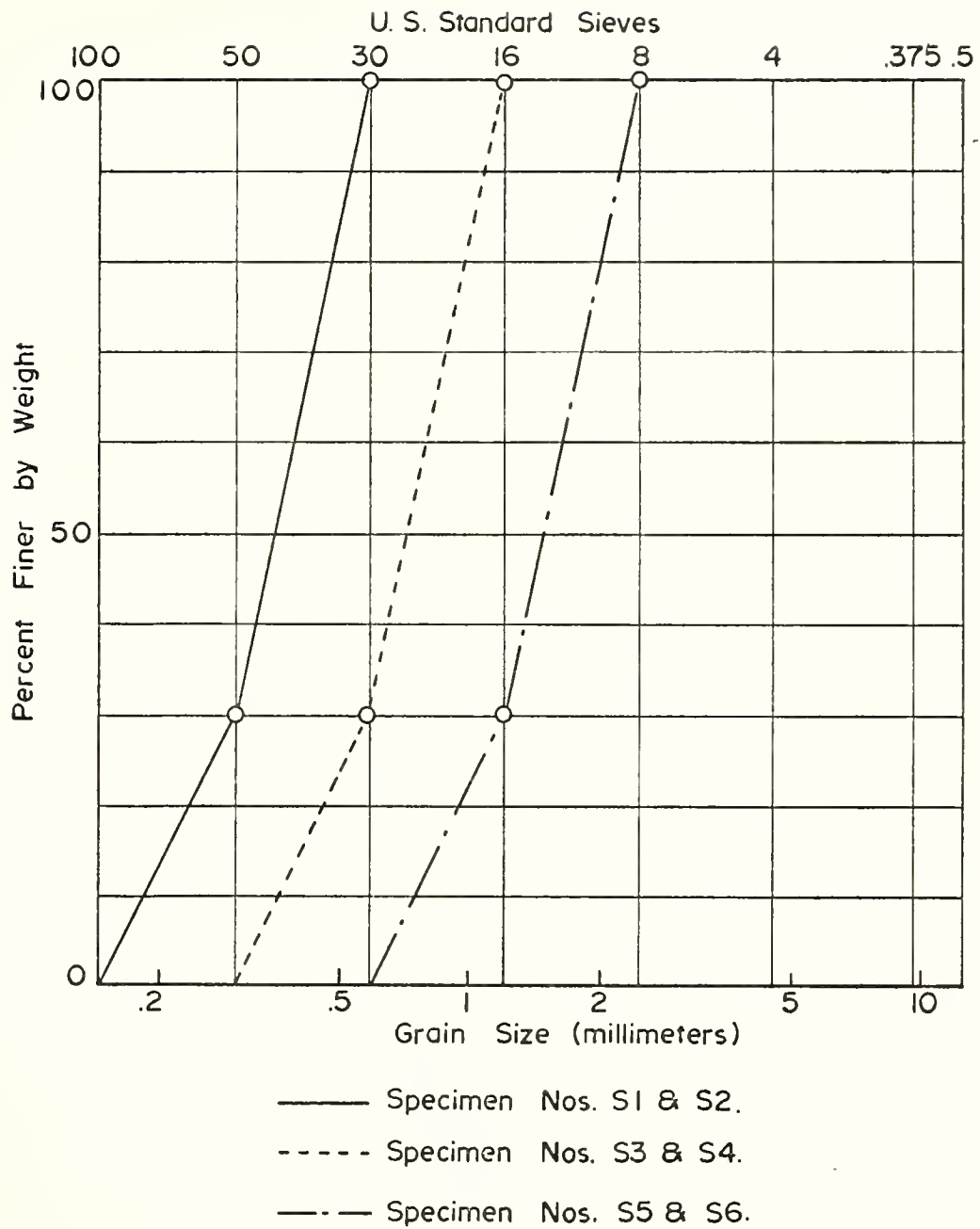


FIGURE 1 - AGGREGATE GRADATION FOR SINGLE-SIZE MIXTURES

Table 3. Aggregate Gradation of Single Size Mixtures

U.S. Sieve Size	Total Percent Passing		
	Specimen No.		
	S1, S2	S3, S4	S5, S6
1/2 in			
3/8 in			
No. 4			
No. 8			100
No. 16		100	30
No. 30	100	30	0
No. 50	30	0	
No. 100	0		

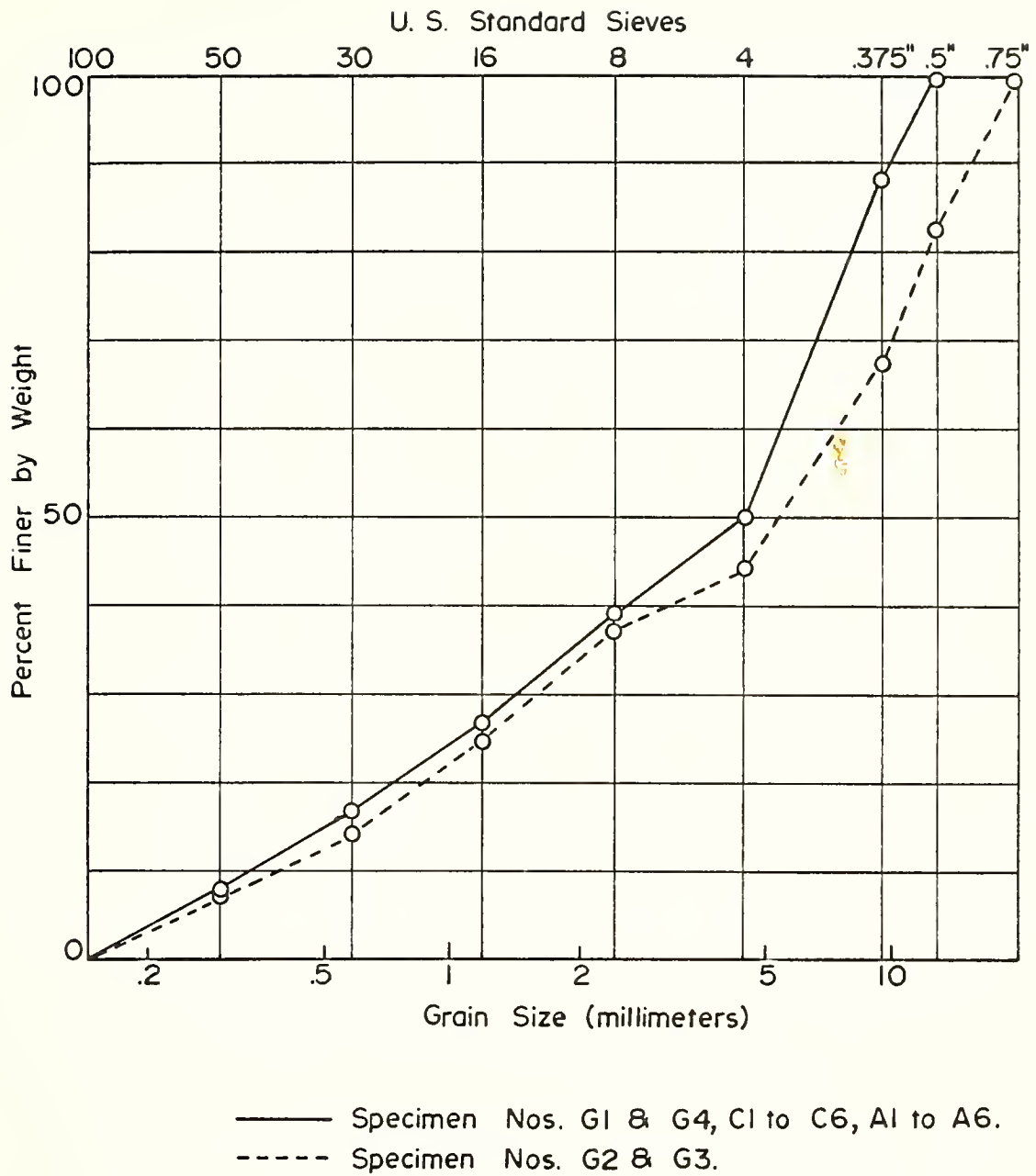


FIGURE 2 - AGGREGATE GRADATION FOR GRADED MIXTURES

Table 4. Aggregate Gradation of Graded Mixtures

U.S. Sieve Size	Total Percent Passing	
	Specimen No.	
	G1, G4, C1 to C6, A1 to A6	G2, G3
	(Mid Point, Type B #11)*	(Mid Point, Type A #9)*
3/4 in		100
1/2 in	100	82.5
3/8 in	88.5	67.5
No. 4	50.0	44.0
No. 8	39.0	37.5
No. 16	26.5	24.5
No. 30	16.5	14.0
No. 50	8.0	7.5
No. 100	0.0	0.0

* Reference No. 17, Indiana State Highway Commission

Table 5. Data for Single-Size Specimens

Properties	Specimen No.					
	S1	S2	S3	S4	S5	S6
Batch weight of aggregate, gms	900	900	950	950	1000	1000
% Asphalt by weight of aggregate (a)	4	10	3	9	3	9
Specimen height, in (cm)	2.589 (6.58)	2.562 (6.51)	2.735 (6.95)	2.681 (6.81)	2.592 (6.58)	2.715 (6.90)
No. of gyratory revolutions	25	25	25	25	25	25
Unit weight, lbs/cu. ft. (kg/cu.m)	101.52 (1626.4)	108.27 (1734.5)	105.95 (1697.3)	111.51 (1786.4)	109.59 (1755.6)	115.23 (1846.0)
% Air voids (total calculated) (b)	35	25	33	23	31	21
Permeability, cm. per sec. (c)	3.69×10^{-7}	2.41×10^{-7}	6.29×10^{-7}	6.32×10^{-7}	6.23×10^{-6}	1.02×10^{-6}
% Asphalt absorption (d)	0.823	0.823	0.762	0.762	0.707	0.707
% Asphalt available for aggregate coating (e) = (a) - (d)	3.177	9.177	2.238	8.238	2.293	8.293
Amount of kerosene retained (f) = Surface area x constant	3.02	3.02	1.69	1.69	0.95	0.95
Film thickness factor (g) = $\frac{e}{f}$	1.05	3.04	1.32	4.87	2.41	8.73
Film thickness factor = $\frac{g}{c}$ Permeability	2.85×10^6	1.26×10^7	2.11×10^6	7.71×10^6	3.87×10^5	8.56×10^6
Film thickness factor = $\frac{g}{b}$ % Air Voids	0.03	0.12	0.04	0.21	0.08	0.42

Table 6. Data for Graded Mixture Specimens (Group G)

Properties	Specimen No.			
	G1	G2	G3	G4
Batch weight of aggregate, gms	1000	1000	1000	1000
% Asphalt by weight of aggregate (a)	4	3	7	8
Specimen height, in (cm)	2.300 (5.84)	2.317 (5.89)	2.250 (5.72)	2.215 (5.63)
No. of gyratory revolutions	25	25	25	25
Unit weight, lbs/cu.ft. (kg/cu.m)	135.50 (2170.7)	134.43 (2153.6)	139.79 (2239.4)	143.31 (2295.8)
% Air voids (total calculated) (b)	14	16	8	4
Permeability, cm. per sec. (c)	3.54×10^{-7}	5.00×10^{-7}	5.00×10^{-9}	5.03×10^{-9}
% Asphalt absorption (d)	0.691	0.662	0.662	0.691
% Asphalt available for aggregate coating (e) = (a) - (d)	3.309	2.338	6.338	7.309
Amount of kerosene retained (f) = Surface area x constant (f)	1.398	1.234	1.234	1.398
Film thickness factor (g) = $\frac{e}{f}$	2.367	1.895	5.136	5.228
Film thickness factor = $\frac{g}{c}$ Permeability	6.69×10^6	3.79×10^6	1.03×10^5	1.04×10^9
Film thickness factor = $\frac{g}{b}$ % Air voids	0.169	0.118	0.642	1.307

Table 7. Data for Graded Mixture Specimens (Group C)

Properties	Specimen No.					
	C1	C2	C3	C4	C5	C6
Batch weight of aggregate, gms	1000	1000	1050	1050	1110	1110
% Asphalt by weight of aggregate	5.5	5.5	5.5	5.5	5.5	5.5
Specimen height, in (cm)	2.305 (5.85)	2.301 (5.84)	2.320 (5.89)	2.303 (5.85)	2.305 (5.85)	2.316 (5.88)
No. of gyratory revolutions	19	22	53	61	328	472
Unit weight, lbs/cu.ft. (kg/cu.m)	137.22 (2198.3)	137.64 (2205.0)	142.03 (2275.3)	143.02 (2291.2)	152.96 (2450.5)	152.18 (2437.9)
% Air voids (total calculated)	11.1	10.9	8.0	7.4	1.0	1.5
Permeability, cm. per sec.	1.03×10^{-7}	0.89×10^{-7}	1.33×10^{-8}	1.29×10^{-8}	5.45×10^{-9}	4.67×10^{-9}

Table 8. Data for Graded Mixture Specimens (Group A)

Properties	Specimen No.					
	A1	A2	A3	A4	A5	A6
Batch weight of aggregate, gms	1050	1050	1050	1050	1050	1050
% Asphalt by weight of aggregate	3.0	3.0	5.5	5.5	8.0	8.0
Specimen height, in (cm)	2.304 (5.85)	2.307 (5.86)	2.306 (5.86)	2.307 (5.86)	2.309 (5.86)	2.314 (5.88)
No. of gyratory revolutions	150	161	82	86	38	42
Unit weight, lbs/cu.ft. (kg/cu.m)	142.40 (2281.2)	141.84 (2272.3)	144.09 (2308.3)	144.01 (2307.0)	145.84 (2336.4)	145.20 (2326.1)
% Air voids (total calculated)	11.0	11.3	6.7	6.8	2.4	2.9
Permeability, cm. per sec.	1.17x10 ⁻⁷	1.33x10 ⁻⁷	6.87x10 ⁻⁹	6.09x10 ⁻⁹	4.75x10 ⁻⁹	4.76x10 ⁻⁹

Each individual batch of aggregate was thoroughly mixed, placed in the oven and heated to $300 \pm 5\text{F}(149 \pm 3\text{C})$ (except specimen nos. C1 to C6 and A1 to A6). The asphalt was heated separately to $275 \pm 5\text{F}(135 \pm 3\text{C})$ (except specimen nos. C1 to C6 and A1 to A6). Since low asphalt content was planned to be used for some specimens in the series C1 to C6 and A1 to A6, lower temperatures were used in these series. These temperatures were $275 \pm 5\text{F}(135 \pm 3\text{C})$ and $250 \pm 5\text{F}(131 \pm 3\text{C})$, respectively.

To avoid excessive loss of heat during mixing, the mixing bowl and paddle were preheated to $250 \pm 5\text{F}(121 \pm 3\text{C})$. The hot aggregate was transferred to the mixing bowl and a crater was formed in the center. The bowl was then placed on the Mettler top loading balance (Model P11N), tared and the desired amount of asphalt (to the nearest one-tenth of a gram) was added. The aggregate and the asphalt were mixed in the Hobart Electric Mixer (Model N-50) for two minutes. The batch was then ready for compaction.

The gyratory testing machine (GTM) was used for compaction. This machine (20), developed by the Waterways Experiment Station, Vicksburg, Mississippi, is based on a compaction technique devised by the Texas Highway Department. It has been demonstrated that the simulation of field compaction and traffic densification is both feasible and practical in the laboratory through the use of this machine (21).

The machine was set for a gyratory angle of 1 degree and a vertical pressure of 100 psi (7.03 kgf per sq. cm.). The GTM fixed roller was used. The above settings were based on the ASTM tentative testing method (22), except that a vertical pressure of 100 psi

(7.03 kgf per sq. cm.) was used instead of 200 psi (14.06 kgf per sq. cm.). This was done in order to reduce the amount of aggregate degradation. The GTM heater was set at $140 \pm 5^{\circ}\text{F}$ ($60 \pm 3^{\circ}\text{C}$) and was switched on one hour before starting the specimen compaction. To avoid loss of heat during compaction, the mold and the base plate were preheated to $250 \pm 5^{\circ}\text{F}$ ($121 \pm 3^{\circ}\text{C}$).

The heated mold, base plate and a paper disc were placed on the carrying tray. The prepared bituminous mixture contained in the mixing bowl was then transferred into the mold with a spoon in a manner to avoid hand trowelling or tamping, and a paper disc was placed on top of the mixture. With the help of the carrying tray, the mold containing the mixture was placed in the GTM and the vertical pressure was applied. After clamping the mold in the mold chuck, the roller carriage was actuated. Each specimen was compacted with the desired number of gyratory revolutions (Tables 5 to 8). Immediately following the compaction, the specimen was leveled using the GTM leveling mechanism.

The compacted specimen contained in the mold was then removed from the GTM and allowed to cool at room temperature (70 to 75°F ; 21.1 to 23.9°C) until no deformation would result while removing it from the mold (about 6 hours). The cooled specimen was extruded, allowed to cool further at room temperature, and then weighed. The specimen was now ready for further testing.

Six specimens (nos. S1 to S6) were prepared under the group, 'single-size mixtures'. The data for these specimens are given in Table 5.

The 'graded mixtures' were subdivided into the following three groups based on compactive effort, asphalt content and aggregate density:

Group G: The specimens in this group had varying asphalt content and aggregate density, but they were made with the same compactive effort. Six such specimens were prepared, but two were rejected due to deformation. The data for the four specimens (nos. G1 to G4) are given in Table 6.

Group C: The specimens in this group were made with varying compactive effort and aggregate density but had the same asphalt content. Three levels of compactive effort, high (about 1 to 2 percent total air voids), medium (about 7 to 8 percent total air voids), and low (about 11 percent total air voids) were selected. In order to achieve approximately the same height for all the specimens, trial runs were made with varying aggregate batch weights. Duplicate specimens for each level were prepared (nos. C1 to C6). The data for these specimens are given in Table 7.

Group A: The specimens in this group had varying asphalt content but had the same aggregate density. This was achieved by varying the compactive effort. Three levels of asphalt content, low (3.0 percent by weight of aggregate), medium (5.5 percent by weight of aggregate), and high (8.0 percent by weight of aggregate) were selected. Duplicate specimens were prepared for each level of

asphalt content (nos. A1 to A6). Table 8 presents the data for these specimens.

Single-size mixture and graded mixture (Group G) were designed in order to study the effect of film thickness, voids and permeability on asphalt hardening.

Graded mixtures (Groups C and A) were designed primarily to study the applicability of the test procedure from the standpoint of evaluation of mixture's resistance to asphalt hardening. (Refer to 'Application of Durability Evaluation' under 'Results and Their Analysis'.) They were also utilized along with graded mixture (Group G) to study the mixture property parameters that influence asphalt hardening in graded mixtures.

The preparation, oxidation and testing of the specimens were in the following order:

1. Single-size mixtures; The specimens were prepared and then subjected to alternate cycles of oxidation and testing. The order of preparation and testing was completely randomized.
2. Graded mixture (Group G); The specimens were prepared and then subjected to alternate cycles of oxidation and testing. The order of preparation and testing was completely randomized.
3. Graded mixtures (Groups C and A); Six specimens were first prepared choosing one from each of the three levels of compactive effort (nos. C1, C3 and C5 in Group C) and asphalt content (nos. A1, A3 and A5 in Group A). The order of preparation of these six specimens was completely randomized. The remaining six specimens (nos. C2, C4, C6, A2, A4 and A6),

chosen in a random order, were prepared the following day. These two sets (6 specimens in each set) were simultaneously exposed to accelerated oxidation and tested. When one was being oxidized the other was in the process of testing. The order of testing in each set was completely randomized.

TEST PROCEDURE

The various measurements and tests carried out on each specimen, after its preparation, are described in this section. The sequence of presentation is as follows: Permeability Measurement, Asphalt Film Thickness, Creep Test as a Measure of Asphalt Hardening, and Oxidation of Compacted Asphaltic Mixture Specimens.

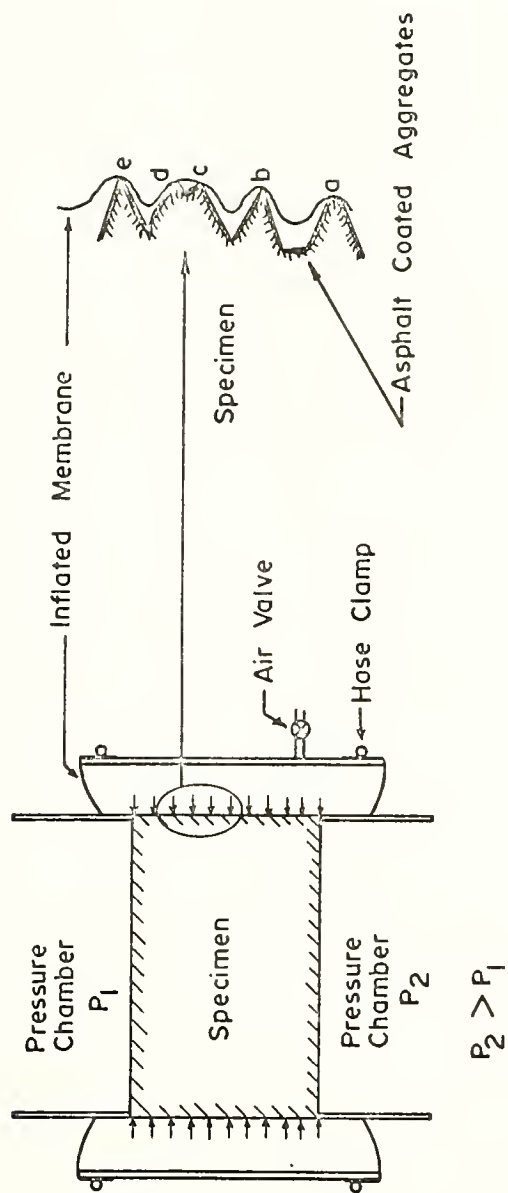
Permeability Measurement

Various air permeability measurement techniques have been used in the past (7, 13, 23, 24, 25). In 1973, Gilbert and Keyser (26) conducted a study of the currently used methods for determining the permeability of bituminous mixtures. They reported that 15 types of permeameters were currently in use in North America and Europe at that time. Of these, nine can be used in the laboratory. Based on the above information and the objectives of the study, it appeared that an air permeability test would be best suited for the permeability measurement. If water were to be used, the specimen would become saturated and would have to be completely dried before any further testing. This would complicate the testing unduly and would introduce another factor into the study. Also, the data obtained by air measurement would be more realistic for the objectives of this project as compared to a water permeability measurement.

In general, air permeability is measured by creating a known pressure differential across the specimen and measuring the amount of air flow for a known period of time. This is usually achieved by placing the specimen in a cylindrical rubber membrane which has been fastened to a hollow metallic cylinder with hose clamps (Figure 3A). The membrane is then inflated with sufficient pressure to prevent air from passing between the walls of the specimen and the membrane during the permeability measurement.

Viewing this macroscopically the idea seems to be sound, but when the specimen surface-membrane contact is observed microscopically (Figure 3B) the following points arise:

1. The membrane may contact only the high points of the aggregates (for example, points a, b, c, d and e in Figure 3B). If so, air could pass between the specimen surface and the membrane. This would result in a permeability value higher than the true value.
2. The gradation of the mixture plays an important role. Specimen-membrane contact will be less for coarse mixtures and more deviation from the true value of permeability may result.
3. Inflation pressure in the membrane is important. If the pressure is low, the specimen-membrane contact will be less. If the pressure is excessive the specimen may deform, especially when it is of low density or if the binder is of low viscosity.
4. The thickness of the membrane is important. A thick membrane will result in less specimen-membrane contact. If the membrane



A) A General View B) Surface Contact as Viewed Microscopically

FIGURE 3 - PERMEABILITY MEASUREMENT OF COMPACTED ASPHALTIC MIXTURES USING RUBBER MEMBRANE

is too thin it will bulge near the hose clamps, thus increasing the probability of its bursting.

The above points clearly indicate that it is difficult for the experimenter to visualize the extent of specimen-membrane contact area for any set-up. As described earlier, when using this assembly, the amount of air flow through the specimen is measured at a certain pressure differential across it, which in turn is used to calculate the permeability of the compacted bituminous mixture. Theoretically, the true permeability value of this compacted mixture should be obtained from the summation of the air flowing through each channel in the specimen. In the above set-up, the amount of air flow measured is the sum of the air flowing through each channel plus the amount flowing between the specimen wall and the membrane. Therefore, a permeability value higher than the true value is measured if air passes between the specimen wall and the membrane. In general, the greater the specimen surface-membrane contact area, the closer the results will be to the true permeability value. Since this contact area is dependent on so many factors, especially when coarse mixtures are concerned, it may be rather difficult for one to obtain the true value of permeability with this set-up.

In order to provide reliable values of permeability, Goode and Lufsey (13) used paraffin as a seal to prevent leakage of air between the sides of the specimen and the membrane. Prior to asphalt extraction, they discarded the outer 1/4 in. (0.64 cm.) of the specimen with the intent of eliminating contamination of paraffin in the extracted asphalt. Even then, they found sufficient contamination to make

the results of the tests on these extracted asphalts useless.

In this study the author used a method that eliminates the above-mentioned problems. The idea in general is to replace the membrane with a rubber coating all around the specimen. The procedure briefly is as follows. (For details, refer to Appendix A.)

The asphaltic mixture specimen whose permeability is to be determined is placed on the specimen supporter, which is a part of the lower assembly (Figures A1 to A4 in Appendix A). The specimen wall is then coated with silicone rubber sealer to a height of about 1 inch (2.5 cm.) from the top (Figure A5). This sealer, made by Dow Corning, is a one-part silicone rubber that is permanently flexible and waterproof (27). It is available in the form of a paste and can easily be applied with the help of a spatula. After the applied material has been partially cured (approximately 8 hours), the specimen is turned upside down and the remaining wall area is coated so that it is sealed to the upper collar (Figure A6).

After the coating has cured (approximately 12 hours), the cover plate is fastened to the upper collar with the help of flynuts (Figure A7). In order to make sure that there are no leaks along the sides of the specimen, air pressure slightly higher than the maximum anticipated to be used in the permeability measurement is applied across the specimen (Figure A8). The air passes through the specimen and starts bubbling from the openings in the lower collar (Figure A9). In case there are any leaks, air bubbles will also show up from places other than the openings in the lower collar. Suitable repairs can easily be made followed by a recheck.

After ensuring that there are no leaks, the specimen is conditioned for creep testing as explained in the section 'Creep Testing as a Measure of Asphalt Hardening'. Then its height is measured (Figure A10). The specimen is now ready for permeability measurement. A known pressure difference is created across the specimen by use of a vacuum, and the rate of air flow is determined by observing the position of the ball in the flowmeter (Figure A11). In this way the rate of air flowing through the specimen is obtained at various differential pressure values. The flow rate so obtained is plotted against the pressure difference. The slope of the straight portion of the curve is calculated using the linear regression equation (28). Using this slope value, specimen height, specimen area and some other constants, the permeability can easily be calculated (Appendix A). This technique has the following advantages:

1. It measures the true permeability value.
2. It eliminates various variables such as:
 - i). selection of membrane thickness, and
 - ii). selection of inflation pressure.
3. It avoids the possibility of specimen deformation.
4. It has a broad application such as:
 - i). The permeability value can be obtained for both very coarse and very fine single-size mixtures (Figure 4).
 - ii). The permeability value can be obtained for mixtures made with low viscosity asphalts since deformation is arrested by the coating.



COARSE
(#4 - #8)

FINE
(#50 - #100)

FIGURE 4 - SINGLE-SIZE COMPACTED MIXTURES



FIGURE 5 - EASILY PEELABLE COATING WITH NO ASPHALT
CONTAMINATION

5. Since the slope value of the plot between rate of air flow vs pressure difference across the specimen is used for permeability calculations, it eliminates the need for adjusting the zero error.
6. It eliminates the possibility of using incorrect data (data in the turbulence range, reference no. 29) since only the slope of the straight line portion of the curve is used in the calculations.
7. It eliminates asphalt contamination as no silicone sticks to the specimen when the layer is peeled from the specimen (Figure 5).
8. The assembly so prepared for permeability measurement can be very effectively used for laboratory simulation of the weathering of asphalt due to air movements in the pavement.

Tables B1 to B4 (Appendix B) present the rate of air flow vs pressure difference across the specimen for single-size and graded mixtures. These values are plotted in Figures B1 to B13 (Appendix B). The slopes of the straight line portion of the curves were obtained by linear regression (28) and are given in Tables B1 to B4 (Appendix B). The slope and specimen height values were then inserted into the following permeability formula:

$$K = 3.812 \times 10^{-11} \times S \times H$$

where:

K = permeability, cm. per sec.

S = slope of the straight line portion of the curve, ml. per min. in.

H = height of the specimen, inches

(For details as to how this formula was obtained, refer to Appendix A).

The above formula is for a testing temperature of 68F(20C). Suitable modifications were made for different testing temperatures (Appendix A).

The permeability values of the single-size and graded mixtures are given in Tables 5 to 8.

Asphalt Film Thickness

In order to find the average thickness of asphalt film on the aggregate, the technique generally employed is to obtain the ratio of the quantity of asphalt to the surface area of the aggregate. The surface area is generally calculated by multiplying certain constant factors by the percentages of total aggregate passing certain sieve sizes for any particular gradation. The sum of products gives the surface area of the aggregate having that particular gradation (13). In such a procedure no consideration is given to the character of the surface nor to the absorptive capacity of the aggregate. This means that the usual procedure calculates the film thickness based on both absorbed and adsorbed asphalt. It would be more appropriate to calculate the film thickness based on (i) only the portion of the asphalt that is available for aggregate coating and (ii) the true surface area of the aggregate.

In order to obtain the portion of total asphalt that is available for aggregate coating in an asphaltic mixture, it is necessary to know the amount of asphalt that will be absorbed by the aggregate. Therefore, the amount of asphalt absorption for each sieve size fraction of the

aggregate was first obtained using the Vacuum Pycnometer (18). This was achieved by mixing separate batches of single-size aggregate (for each sieve size fraction) with enough asphalt to coat all the pieces. These batches were then subjected to the vacuum-saturation technique (18). Briefly, the procedure consisted of employing vacuum to remove all the free air from the sample of bituminous mixture under water and then measuring the volume of the voidless mass by water displacement. Utilizing the above information and the specific gravity of the aggregate and that of the asphalt, the percent asphalt absorption values were obtained for each sieve-size fraction of the aggregate. The results are presented in Table 1A. See section on 'Materials and Specimen Preparation'. The difference between the total amount of asphalt in the mixture and the amount that was absorbed by the aggregate gives the portion of the asphalt that was available for aggregate coating.

The Centrifuge Kerosene Equivalent (CKE) Test was used to determine the surface area of the aggregates since it furnishes a measure of their surface capacity (19). The amount of kerosene retained for each sieve-size fraction of the aggregate was obtained separately and is given in Table 1B.

It has been thought that the amount of kerosene retained by the aggregate in the CKE Test represents the sum of the amount absorbed by the aggregate and the amount on the aggregate as a coating. However, the results show (Table 1B) that the percent kerosene retained is much less than the percent water absorption for coarse aggregate sizes (retained U.S. sieve size no. 8). For fine-size aggregates there is

not much difference between the percent water absorption values for various sieve sizes whereas percent kerosene retained values increase considerably with decrease in aggregate size. This indicates that the amount of kerosene absorbed by the aggregates may be negligible. It may be due to the fact that time for absorption in the CKE test is very short.

Therefore, the amount of kerosene retained by the aggregates was considered to be directly proportional to their surface area assuming the film thickness of kerosene to be constant. When compared, the surface area values determined in this way fall very close to the values obtained by using the surface area factor equation (Table 1B). This also supports the theory of negligible kerosene absorption by the aggregates in the CKE test. The asphalt film thickness factor was calculated as follows:

$$\begin{aligned}\text{Film Thickness Factor} &= \frac{\text{Percent asphalt available for aggregate coating}}{\text{Surface area of the aggregate}} \\ &= \frac{a - d}{f}\end{aligned}$$

where:

a = percent asphalt by weight of aggregate in the mix,

d = percent asphalt absorption by aggregates in the mix, and

f = amount of kerosene retained.

The calculated asphalt film thickness values of single-size and graded mixtures are given in Tables 5 to 8.

Creep Test as a Measure of Asphalt Hardening

The hardening of asphalt in asphaltic mixtures as a result of weathering usually is measured by destructive testing. The procedure has been to extract the asphalt and carry out tests such as penetration, viscosity, softening point and ductility on the recovered asphalt. Theoretically, only the quantity of asphalt that is in contact with air in the asphaltic concrete is oxidized in the weathering process. In the usual procedure when tests are carried out on the recovered asphalt, an average value of the affected and unaffected asphalt is obtained. Logically speaking, only the degree of hardening of the asphalt influencing the stiffness of the mixture should be of concern.

It was felt that a non-destructive compression creep test would be a good indirect measure of the degree of meaningful asphalt hardening that occurs in an asphaltic specimen due to weathering. In this test a constant compressive load is applied to the specimen and axial deformation is measured as a function of time.

Strain under constant stress is a measure of stiffness. For a stiffer mix, the strain will be less. The stiffness of the mix is directly related to asphalt hardening. The mix will be stiffer for a harder asphalt (30). Finally, asphalt hardening is related to mixture durability; as the degree of asphalt hardening increases, mixture durability decreases. Based on this reasoning, it seemed logical to use the creep test as an indirect measure of asphalt hardening. The equipment for the creep test consisted of a loading frame, means for loading and unloading the specimen, a pressure gauge for measuring

load, and a strip chart recorder. A general view of the set-up is shown in Figure 6.

The load was applied with the help of a double-acting type air cylinder using compressed air. Two Sanborn Linearsyn linear variable differential transformers (LVDT's) were used to sense the axial deformation of the specimen. They were placed equidistant from the central axis of the specimen and directly opposite to each other. This was done in order to obtain an average value of the specimen axial deformation. The specimen and LVDT holder assembly is shown in Figure 7.

Changes in output voltage from the LVDT's were amplified and recorded by an 8-channel Sanborn recorder. (Only 2 channels were used in this study.) Calibration of the LVDT's was achieved by displacing the core of the LVDT with a precision micrometer and relating this displacement to the magnitude of the pen deflections of the recorder.

The entire testing was carried out in a temperature-controlled room at 70F(21.1C) (tolerance ± 3 F). This temperature falls within the temperature limits of 60F(15.6C) to 95F(35C) as suggested by Traxler (31). He investigated the best temperature to measure viscosity for evaluation of asphalt durability in service and writes:

"....., thus, we conclude that technically any temperature within the limits shown could be used satisfactorily for evaluating the hardening of the various asphalts during service."

After the specimen was prepared, coated and checked for any leaks (as detailed in section 'Permeability Measurement'), it was subjected to repeated cycles of loading-unloading in the creep-test apparatus

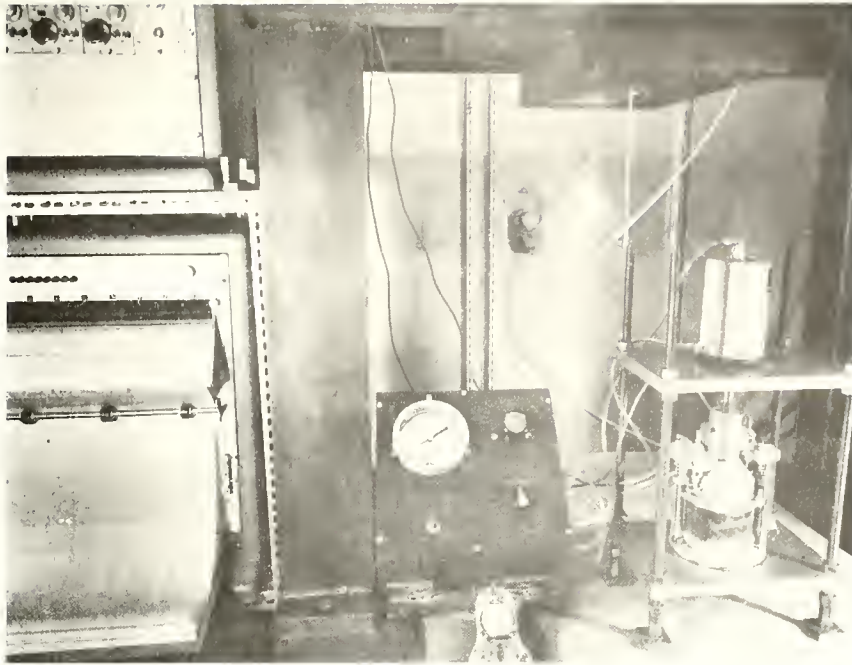


FIGURE 6 - THE CREEP TEST, A GENERAL VIEW

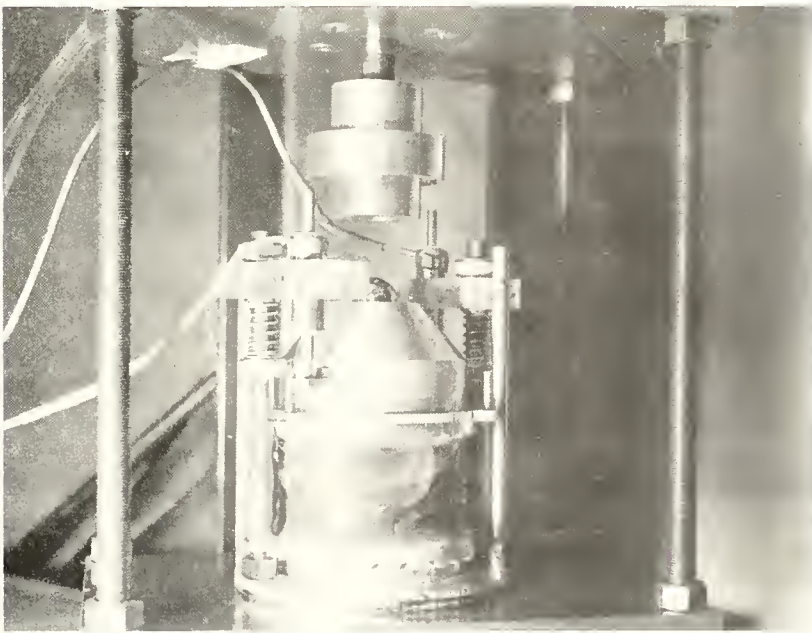


FIGURE 7 - CREEP TEST SPECIMEN AND LVDT HOLDER ASSEMBLY

at 70F(21.1C) (Figure 7). This was done to neutralize any strains that might have developed at the time of specimen extrusion and to condition the specimen for testing. In carrying out this procedure, the test heads were lightly lubricated with silicone grease and the specimen was placed in position. A seating load of 1 psi (0.070 kgf per sq. cm.) was applied followed by 10 cycles of loading and unloading with a conditioning load of 10 psi (0.703 kgf per sq. cm.). Each loading cycle was of one minute duration followed by one minute of unloading. The sequence of operation is given in Table 9.

After specimen conditioning and permeability measurement (described in section 'Permeability Measurement'), the specimen was placed overnight in the temperature control room at 70F(21.1C). The specimen was then ready for creep testing the following day.

In performing the creep test, each specimen was mechanically conditioned (i.e. subjected to specified repeated-load applications). It was demonstrated by Pagen and Ku (32) and Pagen (33) that if response is measured after a number of load applications, the behavior of the material tends to be more reproducible and linear viscoelastic theory may be more appropriately used to define the behavior of asphaltic mixtures. A seating load of 1 psi (0.070 kgf per sq. cm.) was applied, followed by a testing load of 5 psi (0.350 kgf per sq. cm.). The specimen was subjected to 10 cycles of loading and unloading of the testing load. In general, specimen response became quite reproducible after about 8 cycles. A typical curve is presented in Figure 8. This was followed by a load application of 5 psi (0.350 kgf per sq. cm.), and the response of axial deformation was recorded on the graph for

Table 9. Specimen Conditioning Schedule

Recorder Setting	Conditioning Load 10 psi (0.703 kgf per sq cm)		Elapsed Time in Minutes		Remarks
	Load	Unload	Time in Minutes	in Minutes	
0.50 volts/centimeter	x		1	0	
		x	1	1	
	x		1	2	
		x	1	3	
	x		1	4	
		x	1	5	
	x		1	6	
		x	1	7	
	x		1	8	
		x	1	9	
	x		1	10	
		x	1	11	
	x		1	12	
		x	1	13	
	x		1	14	
		x	1	15	
	x		1	16	
		x	1	17	
	x		1	18	
		x	1	19	
				20	

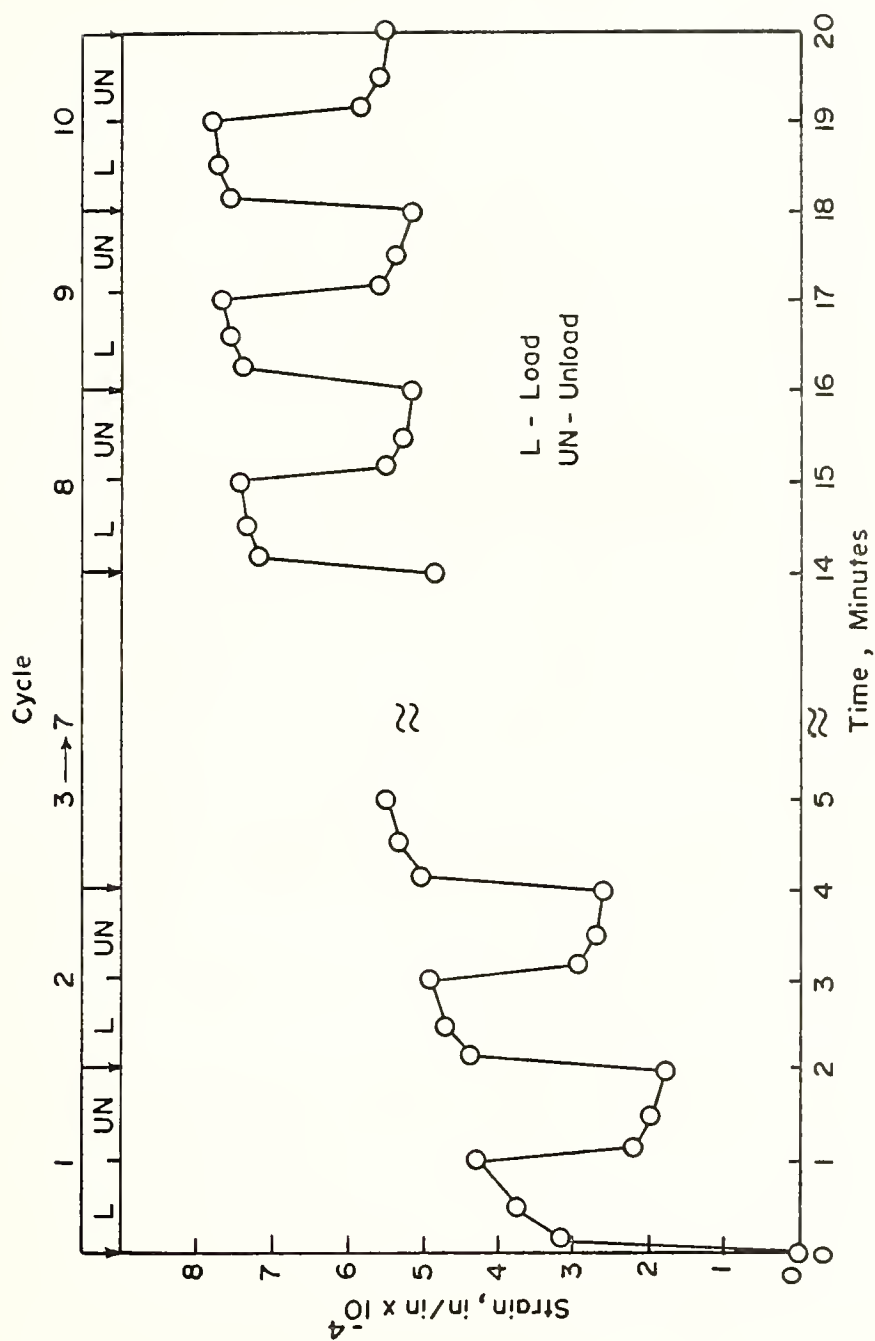


FIGURE 8 - TYPICAL RESPONSE OF SPECIMENS SUBJECTED TO MECHANICAL CONDITIONING

5 minutes. The specimen was then unloaded. This entire sequence is presented in Table 10.

Each specimen was subjected to creep testing after every oxidation cycle (to be explained in the following section, 'Oxidation of Compacted Asphaltic Mixture Specimens') so that variations in creep response due to progressive asphalt hardening could be recorded.

Strain values were calculated from axial deformation and specimen height for various time intervals. The values so calculated for all the specimens are given in Tables C1 to C11 (Appendix C), and the creep curves are plotted on log-log scale in Figures C1 to C11 (Appendix C).

The upper and the lower parallel flat heads of the loading set-up (through which constant compression load was applied) were lightly lubricated with silicone grease before specimen conditioning and creep testing. This was done so that no lateral constraint is exerted by the platens and thus barrelling would be minimized.

Oxidation of Compacted Asphaltic Mixture Specimens

Oxidation of asphalt in the absence of light is considered to be the most important factor causing hardening of asphalt. Traxler writes (34):

"Oxidation in the absence of sunlight is probably the most important effect influencing the hardening and loss of binding power of asphaltic cements. It occurs continuously when the bitumen is in contact with air and the rate of oxidation is dependent upon the temperature."

Based on this concept, the specimens in the laboratory were subjected to oxidation by passing air through them in an oven maintained at 140F (60C).

Table 10. Specimen Testing Schedule

Recorder Setting	Testing Load, 5 psi (0.350 kgf per sq cm)			Elapsed Time in Minutes	Remarks
	Load	Unload	Time in Minutes		
0.50 volts/centimeter	x		1	0	
		x	2	1	After unloading change the recorder setting
0.10 volts/centimeter	x		1	3	
		x	1	4	
	x		1	5	
		x	1	6	
	x		1	7	
		x	1	8	
	x		1	9	
		x	1	10	
	x		1	11	
		x	1	12	
	x		1	13	
		x	1	14	
	x		1	15	
		x	1	16	
	x		1	17	
		x	1	18	
	x		1	19	
		x	1	20	
	x		1	21	
		x	1	22	
			4	23	After unloading change the recorder setting
0.05 volts/centimeter	x		5	27	Testing
		x		32	

After the initial creep testing, the specimens were prepared for oxidation. The cover plates were fastened to each specimen with the help of fly nuts (Figures A1 and A7 in Appendix A). The entire group of specimens was then placed in the oven at 140F(60C). All the specimens were connected to a manifold with the help of rubber tubing as shown in Figure 9. One outlet from the manifold led to the vacuum pump, and the other led to an inclined-tube water manometer (Figure 10).

Air was pulled through the entire set of specimens at a constant head of 0.02 inches (0.05 cm.) of water. This low head was chosen in order to avoid turbulence in the air flow through any of the specimens. Since the suction head was the same for all the specimens in all the sets (single-size and graded mixtures) more air passed through those specimens having higher permeability values.

The specimens were oxidized in the oven for a predetermined period of time. They were then taken out, allowed to cool at room temperature for 2 to 3 hours and placed in the temperature control room at 70F(21C) overnight. Creep testing was performed the following day at 70F(21C). After the creep test, the specimens were again placed in the oven for further accelerated exposure to oxygen. Such cycles of exposure and creep testing were continued for a number of days. Single-size mixtures, graded mixtures (Group G) and graded mixtures (Group C and A) were exposed for 18 days, 10 days and 16 days respectively.

The entire sequence of specimen preparation, permeability measurement, creep testing and accelerated oxygen exposure is given in Table 11.

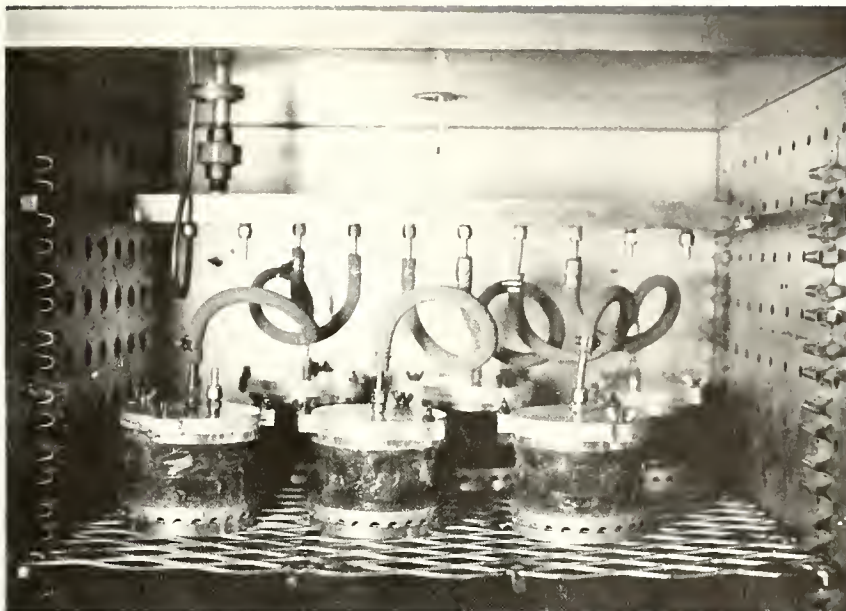


FIGURE 9 - SPECIMENS UNDERGOING ACCELERATED OXIDATION IN THE OVEN

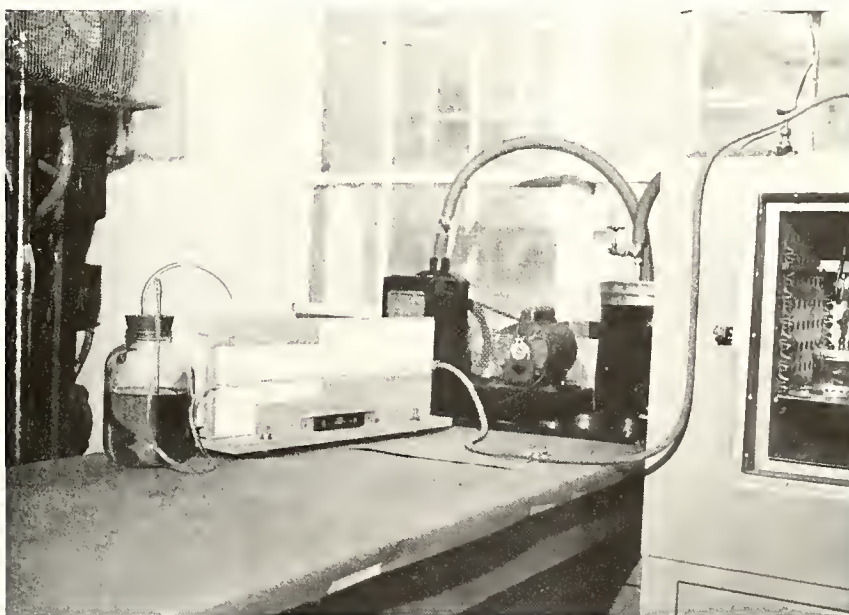


FIGURE 10 - GENERAL VIEW OF ACCELERATED OXIDATION EQUIPMENT

Table 11. Specimen Preparation, Permeability Measurement, Creep Testing and Oxidation Schedule.

<u>Day</u>	<u>Operation</u>
1st Day	Prepare specimen using the Gyrotory Testing Machine.
2nd Day (Morning)	Extrude specimen from the mold, obtain its weight, and coat the specimen and the lower collar with silicone rubber sealer.
2nd Day (Evening)	Turn the specimen upside down and coat the upper collar with silicone-rubber sealer.
3rd Day	Immerse the specimen in water, apply air pressure and check for any leaks. Repair if necessary.
	Do specimen conditioning.
	Do specimen height measurement.
	Do permeability measurement.
	Place the specimen in the temperature control room at 70F (21.1C).
4th Day	Perform the creep test at 70F (21.1C).
	Place the specimen in the oven @ 140F (60C).
	Pass air through the specimen under a suction head of 0.02 inches (0.05 cm) of water.
5th Day	After 24 hours (1 day accelerated oxidation), take the specimen out of the oven, allow it to cool, and then place it in the temperature control room at 70F (21.1C) overnight.
6th Day	Perform the creep test at 70F (21.1C).
	Continue the cycle of oxygen exposure and creep testing for the desired number of days.

RESULTS AND THEIR ANALYSIS

The mixture property parameters (film thickness factor, percent air voids (accessible and total calculated), permeability) and the creep test results of single-size and graded mixtures are utilized in this section for analysis. The sequence of presentation of the various topics studied are as follows: Creep Curve Interpretation, Single-Size Mixtures, Graded Mixtures, Void-Permeability Relationship, Comparison of Recovery and Creep Test Results, and Application of Durability Evaluation.

Creep Curve Interpretation

The changes in slope and intercept values of the creep curves (log strain vs log time plots) resulting from progressive oxidation of the asphaltic mixture specimens were utilized as a measure of asphalt hardening. As asphalt in the mixture hardens, the creep curve slope value increases accompanied by a decrease in the intercept value. This phenomenon was observed in general for all the specimens (Figures C1 to C11 and Tables C12 to C15 in Appendix C). The intercept values of the creep curves were arbitrarily taken at 1 second.

Since the purposes of this study require a measurement of the rate of asphalt hardening, the ratio of the slope (or intercept) of the creep curve after 'X' days of oxidation to the slope (or intercept) of the creep curve at no oxidation was utilized for evaluation. This procedure

eliminates the initial variations in slope and intercept values among specimens of the creep curves at no oxidation. The following terminology is used to designate these ratios:

Durability Index (Slope)

$$= \frac{\text{Creep Curve Slope, 'X' Days Weathering (Oxidation)}}{\text{Creep Curve Slope, No Weathering (Oxidation)}}$$

Durability Index (Intercept)

$$= \frac{\text{Creep Curve Intercept, 'X' Days Weathering (Oxidation)}}{\text{Creep Curve Intercept, No Weathering (Oxidation)}}$$

The calculated values of the two indices for single-size and graded mixtures are presented in Tables C12 to C15 (Appendix C). It should be observed that a higher value of durability index (slope) or lower value of durability index (intercept) indicates less durable mixtures, i.e. more asphalt hardening.

No corrections were made in the creep data due to variations in diameter/height ratios of the specimens. All specimens were 4 in. (12.54 cm.) in diameter and of near-equal height (2.301 to 2.735 in.; 5.84 to 6.95 cm.). Hills (35) has reported that strain in the mix as a function of the loading time is independent of the shape and size of the specimens, provided that the parallel flat ends of the specimens are lubricated so that the platens exert no lateral constraint and 'barreling' is eliminated. These findings are in agreement with those of Hughes et al. (36), who used MGA-pads to avoid constraint. Since both the upper and the lower heads of the loading device were lubricated and height variations were small, it was not felt necessary to make any corrections for variations in diameter/height ratios of the specimens.

Also, it was determined that the silicone rubber coating on the specimens had no significant influence on the creep properties of the mixtures. This conclusion is based on the comparison tests carried out on rubber specimens. The details are presented in Appendix D (Influence of Silicone on Creep Properties).

Single-Size Mixtures

In this section the results based on the testing of single-size mixtures are presented, and the data are analyzed.

Each of the five mixture property parameters; film thickness factor (FTF), permeability (P), percent air voids (total calculated) V, FTF/P and FTF/V (see Table 5) was plotted vs durability index (slope) and durability index (intercept) (See Table C12, Appendix C) for all six specimens. These ten figures (E1 to E10) are presented in Appendix E. The mixture property parameter that correlates best with the durability index should be the mixture property dominating control of resistance to asphalt hardening in the mixture.

Linear regression analyses were used (28) to compare the durability index values and the mixture property parameters. The slope values and the correlation coefficients squared (R^2) are given in Tables 12 and 13. Intuitively, the correlation coefficient value should be large if the degree of association between the two axis parameters is high, and it should be small if the degree of association is low (37). By examining Table 13 for R^2 values, it was difficult to decide which of the five parameters correlated best to the durability index values. Therefore, it was decided to conduct Analysis of Variance Tests (ANOVA).

Table 12. Slope Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Single-Size Mixtures for Various Days of Weathering (Oxidation)

Weathering-Days	Log(FTF)	Log(V)	Log(P)	$\text{Log}(\frac{\text{FTF}}{\text{P}})$	$\text{Log}(\frac{\text{FTF}}{\text{V}})$
For Durability Index (Slope)					
1	-.088	.553	.168	-.165	-.077
2	-.197	.889	.165	-.204	-.163
3	-.057	.396	.145	-.135	-.051
5	-.114	.705	.221	-.217	-.100
18	.088	.049	.381	-.264	.059
For Durability Index (Intercept)					
1	.050	-.203	-.020	.035	.040
2	.067	-.263	-.015	.038	.054
3	.056	-.256	-.024	.041	.046
5	.026	-.133	-.030	.033	.022
18	.027	-.217	-.095	.085	.025

FTF - Film Thickness Factor

V - Percent Air Voids (Total Calculated)

P - Permeability

Table 13. R^2 Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Single-Size Mixtures for Various Days of Weathering (Oxidation)

Weathering-Days	$\text{Log}(\text{FTF})$	$\text{Log}(V)$	$\text{Log}(P)$	$\text{Log}(\frac{\text{FTF}}{P})$	$\text{Log}(\frac{\text{FTF}}{V})$
<u>For Durability Index (Slope)</u>					
1	.085	.235	.636	.784	.103
2	.301	.496	.428	.843	.327
3	.028	.092	.360	.401	.035
5	.071	.188	.543	.668	.085
18	.018	.000	.686	.422	.013
<u>For Durability Index (Intercept)</u>					
1	.295	.338	.093	.368	.303
2	.506	.510	.052	.411	.513
3	.240	.326	.092	.326	.252
5	.127	.212	.331	.532	.139
18	.028	.117	.701	.711	.038

FTF - Film Thickness Factor

V - Percent Air Voids (Total Calculated)

P - Permeability

In order to perform the ANOVA Test, R values were transformed to Z values using the following formula (37, 38):

$$Z = \frac{1}{2} \{ \log_e (1+R) - \log_e (1-R) \}$$

The Z values are presented in Table 14.

The F Test from the ANOVA was applied (28) to the Z values and the results are presented in Table 15. The results show that there is a significant difference between the five mixture property parameters (indicating that some parameters have better correlation than the others) for durability index (slope), but no significant difference was observed for values of durability index (intercept). The Newman Keuls Sequential Range Test (NKSRT) was then conducted (28) on the mixture properties for durability index (slope) in order to find which of the five mixture property parameters were significantly different to the others, i.e. had better correlation. This test also ranks their means in order. The results shown in Table 16 indicate that both the ratio of the film thickness factor to permeability and permeability alone are significantly different to the rest of them at the 5 percent statistical level, but no significant difference exists between the two at this level. Based on the ranked order of means (Table 16), the ratio of film thickness factor to permeability has the highest Z value (i.e. highest correlation coefficient). Permeability has the next highest value. This indicates that the ratio of the film thickness factor to permeability is the best predictor of resistance to hardening for single-size mixtures. Permeability is the next best predictor.

It appears, at this point, that the variations in the slopes of the creep curves due to asphalt hardening may be better indicators of

Table 14. Z Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Single-Size Mixtures for Various Days of Weathering (Oxidation)

Weathering-Days	Log(FTF)	Log(V)	Log(P)	$\text{Log}(\frac{\text{FTF}}{\text{P}})$	$\text{Log}(\frac{\text{FTF}}{\text{V}})$
<u>For Durability Index (Slope)</u>					
1	0.3008	0.5295	1.0903	1.3984	0.3328
2	0.6170	0.8752	0.7823	1.5760	0.6505
3	0.1686	0.3128	0.6931	0.7464	0.1892
5	0.2726	0.4648	0.9439	1.1477	0.3008
18	0.1348	0.0000	1.1817	0.7753	0.1145
<u>For Durability Index (Intercept)</u>					
1	0.6084	0.6640	0.3150	0.7042	0.6184
2	0.8892	0.8953	0.2321	0.7599	0.8994
3	0.5361	0.6490	0.3128	0.6490	0.5520
5	0.3723	0.4973	0.6550	0.9266	0.3919
18	0.1686	0.3564	1.2111	1.2315	0.1975

FTF - Film Thickness Factor

V - Percent Air Voids (Total Calculated)

P - Permeability

Table 15. Analysis of Variance Test Results on Z Values
for Single-Size Mixtures

For Durability Index (Slope)

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	(0.05) F _{crit}
Mix Properties (M)	2.9420	4	0.7355	18.86*	3.01
Oxidation-Days (O)	0.8090	4	0.2022	5.18*	3.01
Interaction (MxO)**	0.6247	16	0.0390		

For Durability Index (Intercept)

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	(0.05) F _{crit}
Mix Properties (M)	0.3950	4	0.0987	1.06	3.01
Oxidation-Days (O)	0.1181	4	0.0295	< 1.00	3.01
Interaction (MxO)**	1.4902	16	0.0931		

* Significant at 5 percent level.

** Non-additivity (28) examined, non-significant.

Table 16. Newman Keuls Sequential Range Test Results on Z Values for Slopes of the Creep Curves for Single-Size Mixtures

Rank	Ranked Order of Means	Ranked Means
1	<u>Film Thickness Factor</u> Permeability	1.1287
2	Permeability	0.9382
3	Percent Air Voids (Total Calculated)	0.4364
4	<u>Film Thickness Factor</u> Percent Air Voids (Total Calculated)	0.3175
5	Film Thickness Factor	0.2987

Table of Differences Between Means

Rank	5	4	3	2
1	.8300*	.8112*	.6923*	.1905
2	.6395*	.6207*	.5018*	
3	.1377	.1189		
4	.0188			

* Significant at 5 percent level.

resistance to hardening than the variations in the intercepts. Statistically, the variations in the intercepts were found to be non-significant at the 5 percent level.

Graded Mixtures

The results based on tests of graded mixtures are presented in this section and the data analyzed.

The experiment involving specimens in Group G was designed in order to examine which one of the five mixture property parameters (film thickness factor (FTF), permeability (P), percent air voids (total calculated) (V), FTF/P and FTF/V) is the best predictor of asphalt hardening in graded mixtures. Accordingly, each of the five mixture property parameters (see Table 6) was plotted vs durability index (slope) and durability index (intercept) (see Table C13, Appendix C) for the four specimens numbered G1 to G4. These plots are presented in Appendix E (Figures E11 to E20). The analysis procedure that was applied was identical to the procedure used for single-size mixtures. The slope values and the correlation coefficients squared (R^2) based on the linear regression analyses are presented in Tables 17 and 18. The transformed Z values from R are given in Table 19.

The F Tests from the ANOVA were applied to the Z values for both durability index (slope) and durability index (intercept). The results indicate (Table 20) that there is no significant difference among the mixture property parameters. This signifies that any one of the five parameters is as good a durability predictor as the other. This conclusion does not seem to be very logical since, according to it, even the film thickness factor is a good predictor of asphalt hardening

Table 17. Slope Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group G) for Various Days of Weathering (Oxidation)

Weathering-Days	Log(FTF)	Log(V)	Log(P)	$\text{Log}(\frac{\text{FTF}}{\text{P}})$	$\text{Log}(\frac{\text{FTF}}{\text{V}})$
<u>For Durability Index (Slope)</u>					
1	-0.949	0.666	0.203	-0.167	-0.415
2	-2.045	1.507	0.403	-0.338	-0.917
4	-3.175	1.621	0.633	-0.529	-1.418
6	-2.641	1.974	0.525	-0.439	-1.193
10	-1.923	1.662	0.397	-0.328	-0.939
<u>For Durability Index (Intercept)</u>					
1	.165	-.116	-.036	.030	.072
2	.226	-.186	-.045	.037	.108
4	.399	-.285	-.083	.069	.176
6	.274	-.208	-.057	.047	.125
10	.209	-.184	-.044	.036	.103

FTF - Film Thickness Factor

V - Percent Air Voids (Total Calculated)

P - Permeability

Table 18. R^2 Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group G) for Various Days of Weathering (Oxidation)

Weathering-Days	Log(FTF)	Log(V)	Log(P)	$\text{Log}(\frac{\text{FTF}}{P})$	$\text{Log}(\frac{\text{FTF}}{V})$
<u>For Durability Index (Slope)</u>					
1	.833	.595	.907	.896	.735
2	.940	.740	.872	.885	.874
4	.972	.604	.921	.931	.895
6	.966	.782	.911	.922	.911
10	.902	.977	.904	.904	.993
<u>For Durability Index (Intercept)</u>					
1	.682	.493	.784	.768	.605
2	.920	.912	.868	.879	.965
4	.959	.709	.988	.985	.862
6	.980	.821	.998	.997	.939
10	.843	.947	.879	.875	.947

FTF - Film Thickness Factor
V - Percent Air Voids (Total Calculated)
P - Permeability

Table 19. Z Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group G) for Various Days of Weathering (Oxidation)

Weathering-Days	Log(FTF)	Log(V)	Log(P)	$\text{Log}\left(\frac{\text{FTF}}{\text{P}}\right)$	$\text{Log}\left(\frac{\text{FTF}}{\text{V}}\right)$
<u>For Durability Index (Slope)</u>					
1	1.5453	1.0228	1.8527	1.8019	1.2819
2	2.0923	1.2934	1.6888	1.7467	1.6967
4	2.4774	1.0378	1.9459	2.0140	1.7923
6	2.3796	1.3938	1.8745	1.9459	1.8745
10	1.8318	2.5550	1.8421	1.8421	3.1063
<u>For Durability Index (Intercept)</u>					
1	1.1754	0.8712	1.3984	1.3583	1.0403
2	1.9333	1.8857	1.6734	1.7211	2.3507
4	2.2729	1.2280	2.9031	2.7587	1.6438
6	2.6467	1.5047	3.8002	3.4534	2.0756
10	1.5762	2.1457	1.7211	1.6967	2.1457
FTF - Film Thickness Factor V - Percent Air Voids (Total Calculated) P - Permeability					

Table 20. Analysis of Variance Test Results on Z Values
for Graded Mixtures (Group G)

For Durability Index (Slope)

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F	F ^(0.05) crit
Mix Properties (M)	1.0389	4	0.2597	1.54	3.01
Oxidation-Days (O)	1.4650	4	0.3663	2.18	3.01
Interaction (MxO)**	2.6906	16	0.1682		

For Durability Index (Intercept)

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F	F ^(0.05) crit
Mix Properties (M)	1.8618	4	0.4654	3.00	3.06
Oxidation-Days (O)	6.1067	4	1.5267	9.87*	3.06
MxO (non additivity)+	2.2460	1	2.2460	14.52*	4.54
Error	2.3206	15	0.1547		

* Significant at 5 percent level.

** Non-additivity (28) examined, non-significant.

+ Reference No. 28.

regardless of the voids or permeability of the asphaltic mixture. That is to say, if specimens are prepared having the same film thickness factor (i.e. the same asphalt content and the same aggregate gradation) the asphalt in them will harden at the same rate irrespective of their void content or permeability (i.e. there is no effect on asphalt hardening due to varying compactive effort). In Group C, specimens were prepared having the same film thickness factor but with varying compactive effort, and the results indicate that the variation in compactive effort has a significant effect upon the asphalt hardening in the mixture. (Refer to the section, 'Application of Durability Evaluation'.)

At this point the asphalt coatings on the aggregates in the specimens were examined closely. It was observed that small size aggregates tend to agglomerate using asphalt as the binding medium. The larger size aggregates seemed to have very little asphalt on them in comparison to the smaller size ones. Thus, it is indicated that the concept of film thickness breaks down in graded mixtures.

Therefore, the three parameters containing the film thickness factor (FTF, FTF/P and FTF/V) were eliminated from the results of Table 19 and only the voids and the permeability were used for comparison. The mean Z values (cell means) based on durability index (slope) and durability index (intercept) for voids are 1.4606 and 1.5271, and for permeability they are 1.8408 and 2.2992 respectively. In both cases, the Z values for permeability are higher than for voids. This indicates that permeability has a better correlation with durability index (slope) and durability index (intercept) than does

voids. Therefore, it can be concluded that permeability is a better predictor of resistance to hardening than is total calculated void content.

These findings led to the decision to explore the void system in the graded mixtures further. The percent air voids (total calculated) in a compacted bituminous mixture is a summation of percent accessible air voids and percent isolated air voids. It was decided that the percent accessible air voids needed to be determined.

After the entire oxidation and creep testing cycles were completed, the lower and upper collars were removed from all the graded mixture specimens with the help of a sharp edge. Specimens at this point had the silicone rubber coating all around them, and special care was taken not to disturb the mixture itself. Each specimen was now weighed. An assembly to support the specimen was put in place (the same one used in the permeability measurement) so that when the specimen was immersed water had access to it from both top and bottom. This assembly consisted of a wire gauze on the specimen supporter which rested on the base plate (Figure A1 and A2 in Appendix A). The specimen was now placed on the wire gauze. This entire set-up is termed the 'specimen assembly'.

The four techniques that were employed to measure the percent accessible air voids in the graded mixtures (Groups G, C and A) are as follows:

1. 24-Hour Soaking: The specimen assembly was immersed in a glass container filled with deaired water. The water level in the container was kept to about 1 inch (2.5 cm), above the

- top of the specimen. After 24 hours the specimen was removed from the water, surface dried and weighed.
2. Hand Pumping: After the above test, the specimen was placed back into the water on the assembly. One hand was now cupped over the sample, and the palm was pumped as a plunger for about 2 minutes. The specimen was then turned upside down and the process was repeated. The specimen was now removed from the water bath, surface dried and weighed.
 3. Under Vacuum (Absolute Pressure, 10 cm. of Mercury): The specimen assembly was placed in a glass jar (dessiccator) filled with deaired water to a height of about 1 inch (2.5 cm.) from the top of the specimen. A vacuum of about 4 inches (10 cm.) of mercury (about a 26-inch (66 cm.) pressure drop) was applied to the inside of the jar for a duration of thirty minutes (39). During this time the jar was gently agitated. After thirty minutes, the vacuum was removed and the inside of the jar was allowed to reach atmospheric pressure. The specimen was maintained submerged in water under atmospheric pressure for another period of thirty minutes. The specimen was then removed from the water, surface dried and weighed.
 4. Under Vacuum (Absolute Pressure 2.5 cm. of Mercury): The specimen was again placed on the assembly in the glass jar containing deaired water. The entire procedure was repeated with the exception that now a vacuum of about 1 inch (2.5 cm.) of mercury (about a 29-inch (73.5 cm.) pressure drop) was

applied. After completing the entire procedure, the specimen was removed from the water, surface dried and weighed.

The entire testing (all four methods) was carried out at room temperature (70 to 75F; 21.1 to 23.9C). Using the amounts of water absorbed by the specimens and their volume, the percent accessible air voids were calculated for all four methods. The results are presented in Table 21.

Each of the six mixture property parameters, permeability, percent air voids (total calculated), percent accessible air voids (24-hour soaking), percent accessible air voids (hand pumping), percent accessible air voids under vacuum (absolute pressure, 10 cm. mercury) and percent accessible air voids under vacuum (absolute pressure, 2.5 cm. mercury) (see Table 21) was plotted vs durability index (slope) and durability index (intercept) (see Tables C13 to C15, Appendix C) for all the groups G, C and A. These plots (Figures E12, E13, E17, E18, and E21 to E52) are presented in Appendix E.

The slopes and the regression coefficients squared (R^2) for the linear regressions between durability index and mixture property parameter are presented in Tables 22 to 27. The Z values calculated from the R values are given in Tables 28 to 30. Analysis of Variance Test (ANOVA) was performed on Z values and the results are presented in Tables 31 to 33.

The F Test results from the ANOVA for both durability index (slope) and durability index (intercept) indicate that there is no significant difference (at the 5 percent level) between the mixture property parameters in terms of better correlation. This was observed for all

Table 21. Percent Air Voids in Graded Mixtures (Groups G, C and A)

Group No.	Specimen No.	Percent Air Voids (Total Calculated)	Percent Accessible Air Voids			
			24 Hr. Soaking	Hand Pumping	Under Vacuum Abs. Pres. 10 cm. Mercury	Under Vacuum Abs. Pres. 2.5 cm. Mercury
G	G1	14.0	3.4	6.0	12.1	12.5
	G2	16.0	4.6	6.6	12.5	12.8
	G3	8.0	2.4	2.8	5.9	6.1
	G4	4.0	1.7	2.1	3.0	3.0
C	C1	11.1	2.4	3.6	8.3	9.3
	C2	10.9	1.6	3.1	7.9	8.8
	C3	8.0	1.0	1.7	6.5	6.9
	C4	7.4	0.8	1.5	5.3	5.9
	C5	1.0	0.5	0.5	0.8	1.0
	C6	1.5	0.2	0.2	0.9	1.2
A	A1	11.0	1.2	2.7	8.6	9.4
	A2	11.3	1.2	2.5	8.5	9.4
	A3	6.7	0.7	1.4	5.2	5.5
	A4	6.8	0.9	1.2	4.5	4.7
	A5	2.4	0.2	0.4	2.2	2.3
	A6	2.9	0.5	0.6	2.2	2.5

Table 22. Slope Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group G) for Various Days of Weathering (Oxidation)

Weathering-Days	Log (Percent Accessible Air Voids)					
	Log(P)	Log(V)	24 Hr. Soaking	Hand	Under Vacuum	Under Vacuum
				Pumping	(Abs. Pres., 10 cm Hg)	(Abs. Pres., 2.5 cm Hg)
<u>For Durability Index (Slope)</u>						
1	0.203	0.666	0.958	0.864	0.654	0.639
2	0.403	1.507	2.432	1.812	1.391	1.357
4	0.633	1.621	3.700	2.820	2.160	2.106
6	0.525	1.974	3.131	2.364	1.830	1.786
10	0.397	1.662	2.400	1.869	1.555	1.527
<u>For Durability Index (Intercept)</u>						
1	-0.036	-0.116	-0.159	-0.153	-0.117	-0.114
2	-0.045	-0.186	-0.285	-0.211	-0.172	-0.168
4	-0.083	-0.285	-0.428	-0.360	-0.274	-0.267
6	-0.057	-0.208	-0.309	-0.253	-0.198	-0.194
10	-0.044	-0.184	-0.257	-0.208	-0.174	-0.171

P - Permeability

V - Percent Air Voids (Total Calculated)

Table 23. Slope Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group C) for Various Days of Weathering (Oxidation)

Weathering-Days	Log(P)	Log(V)	Log (Percent Accessible Air Voids)			
			24 Hr. Soaking	Hand Pumping	Under Vacuum (Abs. Pres., 10 cm Hg)	Under Vacuum (Abs. Pres., 2.5 cm Hg)
			<u>For Durability Index (Slope)</u>			
1	0.036	0.063	0.039	0.035	0.062	0.066
2	0.083	0.176	0.143	0.130	0.169	0.182
4	0.212	0.315	0.256	0.233	0.293	0.320
8	0.291	0.324	0.297	0.245	0.288	0.322
16	0.481	0.564	0.761	0.583	0.553	0.595
<u>For Durability Index (Intercept)</u>						
1	-0.013	-0.027	-0.028	-0.024	-0.028	-0.029
2	-0.027	-0.030	-0.059	-0.041	-0.033	-0.035
4	-0.027	-0.027	-0.040	-0.030	-0.026	-0.029
8	-0.052	-0.052	-0.080	-0.057	-0.050	-0.055
16	-0.078	-0.116	-0.133	-0.107	-0.114	-0.123
P - Permeability						
V - Percent Air Voids (Total Calculated)						

Table 24. Slope Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group A) for Various Days of Weathering (Oxidation)

Weathering-Days	Log (Percent Accessible Air Voids)					
	Log(P)	Log(V)	24 Hr. Soaking	Hand Pumping	Under Vacuum (Abs. Pres., 10 cm Hg)	Under Vacuum (Abs. Pres., 2.5 cm Hg)
	<u>For Durability Index (Slope)</u>					
1	1.477	0.451	0.246	0.406	0.584	0.600
2	0.254	0.001	-0.104	-0.005	0.071	0.058
4	1.537	0.537	0.433	0.517	0.621	0.666
8	0.565	0.097	-0.084	0.061	0.203	0.183
16	2.668	0.867	0.413	0.708	1.111	1.108
<u>For Durability Index (Intercept)</u>						
1	-0.208	-0.066	-0.037	-0.058	-0.084	-0.086
2	-0.090	-0.009	0.027	-0.003	-0.030	-0.025
4	-0.338	-0.104	-0.080	-0.106	-0.128	-0.138
8	-0.208	-0.069	-0.036	-0.057	-0.087	-0.087
16	-0.427	-0.162	-0.118	-0.141	-0.185	-0.191

P - Permeability

V - Percent Air Voids (Total Calculated)

Table 25. R^2 Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group G) for Various Days of Weathering (Oxidation)

Weathering-Days	Log (Percent Accessible Air Voids)					
	Log(P)	Log(V)	24 Hr. Soaking	Hand	Under Vacuum	
				Pumping	(Abs. Pres., 10 cm Hg)	(Abs. Pres., 2.5 cm Hg)
<u>For Durability Index (Slope)</u>						
1	.907	.595	.574	.801	.663	.653
2	.872	.740	.899	.856	.728	.716
4	.921	.604	.893	.890	.753	.741
6	.911	.782	.919	.899	.777	.765
10	.904	.977	.951	.989	.987	.983
<u>For Durability Index (Intercept)</u>						
1	.784	.493	.427	.681	.571	.564
2	.868	.912	.993	.937	.893	.886
4	.988	.709	.747	.904	.756	.744
6	.998	.821	.845	.967	.857	.848
10	.879	.947	.857	.961	.978	.976

P - Permeability

V - Percent Air Voids (Total Calculated)

Table 26. R^2 Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group C) for Various Days of Weathering (Oxidation)

Weathering-Days	Log (Percent Accessible Air Voids)					
	Log(P)	Log(V)	24 Hr. Soaking	Hand	Under Vacuum	Under Vacuum
				Pumping	(Abs. Pres., 10 cm Hg)	(Abs. Pres., 2.5 cm Hg)
<u>For Durability Index (Slope)</u>						
1	.079	.168	.043	.056	.174	.168
2	.279	.777	.356	.474	.769	.763
4	.516	.677	.307	.413	.623	.639
8	.621	.481	.277	.305	.401	.434
16	.691	.591	.785	.743	.639	.637
<u>For Durability Index (Intercept)</u>						
1	.183	.503	.365	.421	.553	.532
2	.304	.234	.625	.505	.306	.291
4	.778	.473	.692	.624	.466	.483
8	.510	.317	.518	.432	.315	.328
16	.634	.863	.789	.825	.897	.891

P - Permeability
V - Percent Air Voids (Total Calculated)

Table 27. R^2 Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group A) for Various Days of Weathering (Oxidation)

Weathering-Days	Log (Percent Accessible Air Voids)					
	Log(P)	Log(V)	24 Hr. Soaking	Hand	Under Vacuum	Under Vacuum
				Pumping	(Abs. Pres., 10 cm Hg)	(Abs. Pres., 2.5 cm Hg)
<u>For Durability Index (Slope)</u>						
1	.947	.785	.335	.733	.922	.889
2	.083	.000	.179	.000	.041	.025
4	.858	.931	.869	.993	.870	.917
8	.212	.055	.060	.026	.171	.127
16	.711	.667	.217	.512	.768	.698
<u>For Durability Index (Intercept)</u>						
1	.932	.832	.374	.746	.942	.902
2	.121	.010	.138	.001	.075	.053
4	.798	.670	.566	.811	.710	.764
8	.755	.737	.286	.583	.819	.756
16	.712	.910	.697	.790	.828	.815

P - Permeability

V - Percent Air Voids (Total Calculated)

Table 28. Z Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group G) for Various Days of Weathering (Oxidation)

Weathering-Days	Log (Percent Accessible Air Voids)					
	Log(P)	Log(V)	24 Hr. Soaking	Hand	Under Vacuum	Under Vacuum
				Pumping	(Abs. Pres., 10 cm Hg)	(Abs. Pres., 2.5 cm Hg)
<u>For Durability Index (Slope)</u>						
1	1.8527	1.0228	0.9915	1.4465	1.1388	1.1212
2	1.6888	1.2934	1.8117	1.6226	1.2670	1.2419
4	1.9459	1.0378	1.7828	1.7645	1.3249	1.2972
6	1.8745	1.3938	1.9333	1.8117	1.3802	1.3540
10	1.8421	2.5550	2.1847	2.9031	2.8257	2.6996
<u>For Durability Index (Intercept)</u>						
1	1.3984	0.8712	0.7805	1.1723	0.9868	0.9752
2	1.6734	1.8857	3.1063	2.0595	1.7828	1.7467
4	2.9031	1.2280	1.3089	1.8421	1.3290	1.3050
6	3.8002	1.5047	1.5825	2.3796	1.6296	1.5956
10	1.7211	2.1457	1.6296	2.2976	2.5988	2.5550

P - Permeability

V - Percent Air Voids (Total Calculated)

Table 29. Z Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group C) for Various Days of Weathering (Oxidation)

Weathering-Days	Log (Percent Accessible Air Voids)					
	Log(P)	Log(V)	24 Hr. Soaking	Hand	Under Vacuum	
				Pumping	(Abs. Pres., 10 cm Hg)	(Abs. Pres., 2.5 cm Hg)
<u>For Durability Index (Slope)</u>						
1	0.2888	0.4356	0.2100	0.2416	0.4441	0.4356
2	0.5874	1.3802	0.6885	0.8442	1.3626	1.3456
4	0.9035	1.1660	0.6241	0.6733	1.0688	1.0958
8	1.0403	0.8556	0.5846	0.6213	0.7464	0.7910
16	1.1913	1.0179	1.4030	1.3011	1.0958	1.0931
<u>For Durability Index (Intercept)</u>						
1	0.4574	0.8852	0.6994	0.7734	0.9594	0.9266
2	0.6198	0.5282	1.0741	0.8892	0.6227	0.6027
4	1.3847	0.8442	1.1946	1.0714	0.8347	0.8576
8	0.8953	0.6372	0.9076	0.7875	0.6343	0.6520
16	1.0876	1.6510	1.4124	1.5160	1.8019	1.7736

P - Permeability

V - Percent Air Voids (Total Calculated)

Table 30. Z Values for the Straight Line Plots Between Durability Index and Various Mixture Property Parameters of Graded Mixtures (Group A) for Various Days of Weathering (Oxidation)

Weathering-Days	Log (Percent Accessible Air Voids)					
	Log(P)	Log(V)	24 Hr. Soaking	Hand	Under Vacuum	Under Vacuum
				Pumping	(Abs. Pres., 10 cm Hg)	(Abs. Pres., 2.5 cm Hg)
<u>For Durability Index (Slope)</u>						
1	2.1457	1.4030	0.6610	1.2782	1.9459	1.7645
2	0.2321	0.0000	0.4513	0.0000	0.2048	0.1593
4	1.6296	2.0140	1.6734	3.1063	1.6811	1.9210
8	0.4973	0.2395	0.2501	0.1624	0.4404	0.3723
16	1.2315	1.1477	0.5049	0.8994	1.3583	1.2044
<u>For Durability Index (Intercept)</u>						
1	2.0140	1.5393	0.7121	1.3089	2.1095	1.8318
2	0.3632	0.1003	0.3896	0.0320	0.2812	0.2342
4	1.4366	1.1538	0.9775	1.4775	1.2315	1.3498
8	1.3290	1.2857	0.5971	1.0058	1.4992	1.3290
16	1.2349	1.8745	1.2044	1.4171	1.5275	1.4883

P - Permeability

V - Percent Air Voids (Total Calculated)

Table 31. Analysis of Variance Test Results on Z Values
for Graded Mixtures (Group G)

For Durability Index (Slope)

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F	(0.05) F crit
Mix Properties (M)	0.7894	5	0.1579	2.18	2.71
Oxidation-Days (O)	5.4820	4	0.3705	18.89*	2.87
MxO (non-additivity)+	0.5442	1	0.5442	7.51*	4.35
Error	1.3781	19	0.0725		

For Durability Index (Intercept)

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F	(0.05) F crit
Mix Properties (M)	2.0261	5	0.4052	1.65	2.71
Oxidation-Days (O)	5.2781	4	1.3195	5.39*	2.87
MxO (non-additivity)+	2.0452	1	2.0452	8.35*	4.35
Error	4.6547	19	0.2450		

* Significant at 5 percent level.

+ Reference No. 28.

Table 32. Analysis of Variance Test Results on Z Values
for Graded Mixtures (Group C)

For Durability Index (Slope)

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F	F ^(0.05) crit
Mix Properties (M)	0.3547	5	0.0709	1.60	2.71
Oxidation-Days (O)	2.4839	4	0.6210	13.99*	2.87
Interaction (MxO)**	0.8887	20	0.0444		

For Durability Index (Intercept)

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F	F ^(0.05) crit
Mix Properties (M)	0.2836	5	0.0567	1.24	2.74
Oxidation-Days (O)	3.2867	4	0.8217	17.90*	2.90
MxO (non-additivity)+	0.1344	1	0.1344	2.93	4.38
Error	0.8719	19	0.0459		

* Significant at 5 percent level.

** Non-additivity (28) examined, non-significant.

+ Reference No. 28.

Table 33. Analysis of Variance Test Results on Z Values
for Graded Mixtures (Group A)

For Durability Index (Slope)

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F	(0.05) F _{crit}
Mix Properties (M)	0.6857	5	0.1371	2.15	2.71
Oxidation-Days (O)	14.5700	4	3.6425	57.77*	2.87
MxO (Non-additivity)+	1.8413	1	1.8413	29.20*	4.35
Error	1.1979	19	0.0630		

For Durability Index (Intercept)

Source	Sum of Squares	Degrees of Freedom	Mean Squares	F	(0.05) F _{crit}
Mix Properties (M)	1.0451	5	0.2090	3.86*	2.71
Oxidation-Days (O)	6.8400	4	1.7100	31.54*	2.87
MxO (non-additivity)+	0.3871	1	0.3871	7.14*	4.35
Error	1.0300	19	0.0542		

* Significant at 5 percent level.

+ Reference No. 28.

the groups G, C and A with one exception in Group A. For the exception, the durability index (intercept) showed a significant difference between the mixture property parameters. Newman Keuls Sequential Range Test was then conducted on the mixture property parameters for the durability index (intercept) in order to find which of the six mixture property parameters were significantly different from the others, i.e. had better correlation. The results, Table 34, indicate that percent accessible air voids (24-hour soaking) is significantly different to the rest of the mixture property parameters at the 5 percent level with the exception of percent accessible air voids (hand pumping). At the 10 percent statistical level, percent accessible air voids obtained by both 24-hour soaking and hand pumping are significantly different from each other. In the ranked order of means, percent accessible air voids (24-hour soaking) shows the lowest Z value, indicating the least degree of association (poor correlation) with durability index (intercept). Therefore, the above test results indicate that percent accessible air voids (24-hour soaking) is not as good a predictor of durability as the other methods tested.

Based on the above analysis, there seemed to be some indication of a relationship between the mixture property parameters. Therefore, it was decided to examine the association between permeability and percent air voids, total calculated and accessible as obtained by using different techniques.

Void-Permeability Relationship

In this section the relationships between various void types and their association with permeability are examined.

Table 34. Newman Keuls Sequential Range Test Results on Z Values for Durability Index (Intercept) for Graded Mixtures (Group A)

Ranked Order of Means	Ranked Means
1. Percent Accessible Air Voids Under Vacuum (Abs. Pres., 10 cm Mercury)	1.3297
2. Permeability	1.2755
3. Percent Accessible Air Voids Under Vacuum (Abs. Pres., 2.5 cm Mercury)	1.2466
4. Percent Air Voids (Total Calculated)	1.1907
5. Percent Accessible Air Voids (Hand Pumping)	1.0482
6. Percent Accessible Air Voids (24-Hour Soaking)	0.7761

Table of Differences Between Means

Rank	6	5	4	3	2
1	.5536**	.2815	.1390	.0831	.0542
2	.4994**	.2273	.0848	.0289	
3	.4705**	.1984	.0559		
4	.4146**	.1425			
5	.2721*				

* Significant at 10 percent level.

** Significant at 5 percent level.

Plots between percent accessible air voids and percent air voids (total calculated) for graded mixtures, Groups G, C and A, are presented separately in Figures 11, 12 and 13. Figure 14 shows the plot for all the groups combined.

In order to investigate the relationship between permeability and percent air voids for graded mixtures, plots were made between the two and are presented for each group in Figures 15 to 17. A plot for all the graded mixture specimens combined (Groups G, C and A) is shown in Figure 18. Linear regression analyses were made between the permeability and air void parameters. Slope, correlation coefficient squared (R^2) and Z values are presented in Table 35. The correlation coefficient is a measure of the degree of association between the two variables (37). It should be large when the degree of association is high and small when the degree of association is low. The results indicate (Table 35) that R^2 values for all the three groups are fairly high (0.8 and higher) with the exception of percent accessible air voids (24-hour soaking) in Group A. The R^2 value in that case is 0.72.

Thus, it can be concluded that percent air voids (total calculated and accessible) are associated with permeability. This confirms the hypothesis presented in the earlier section 'Graded Mixtures', suggesting the possibility of some relationship between the mixture property parameters. The data were further analyzed to see if there existed any significant difference between the R^2 values for the five types of percent air voids (total and accessible), and if so, which one is best related to permeability.

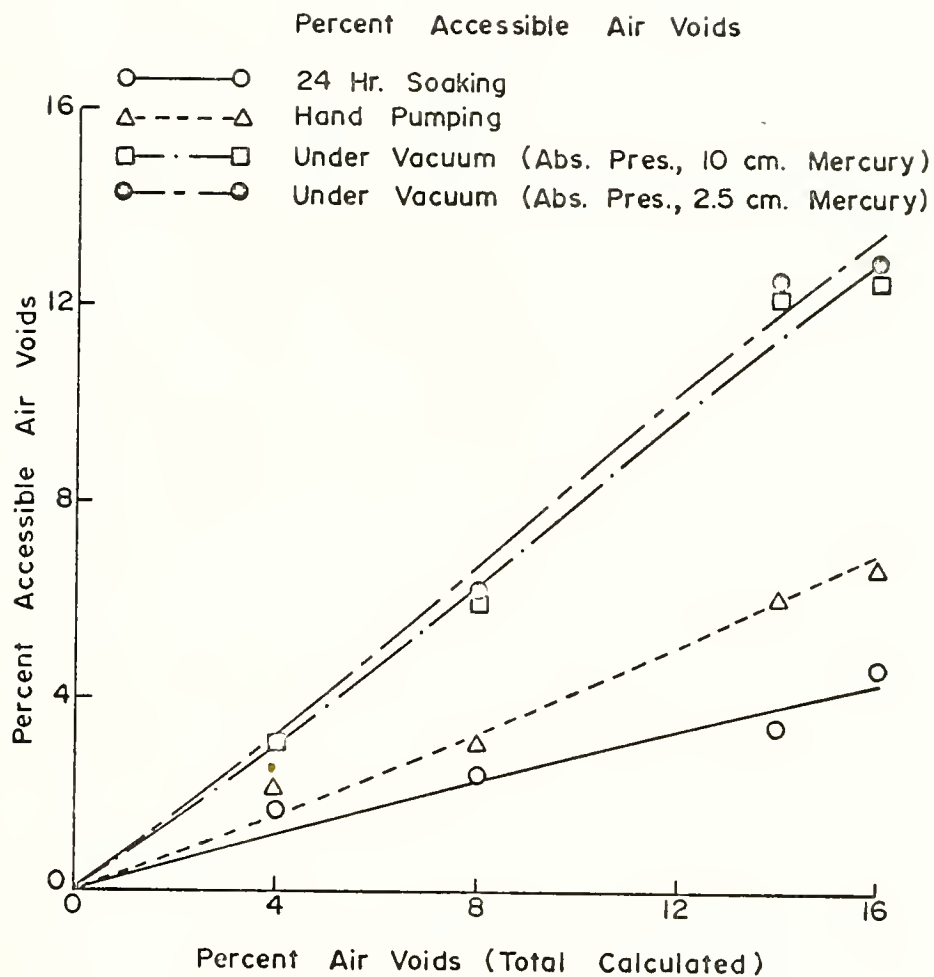


FIGURE 11 - PERCENT ACCESSIBLE AIR VOIDS VS PERCENT AIR VOIDS (TOTAL CALCULATED) FOR GRADED MIXTURES (GROUP G)

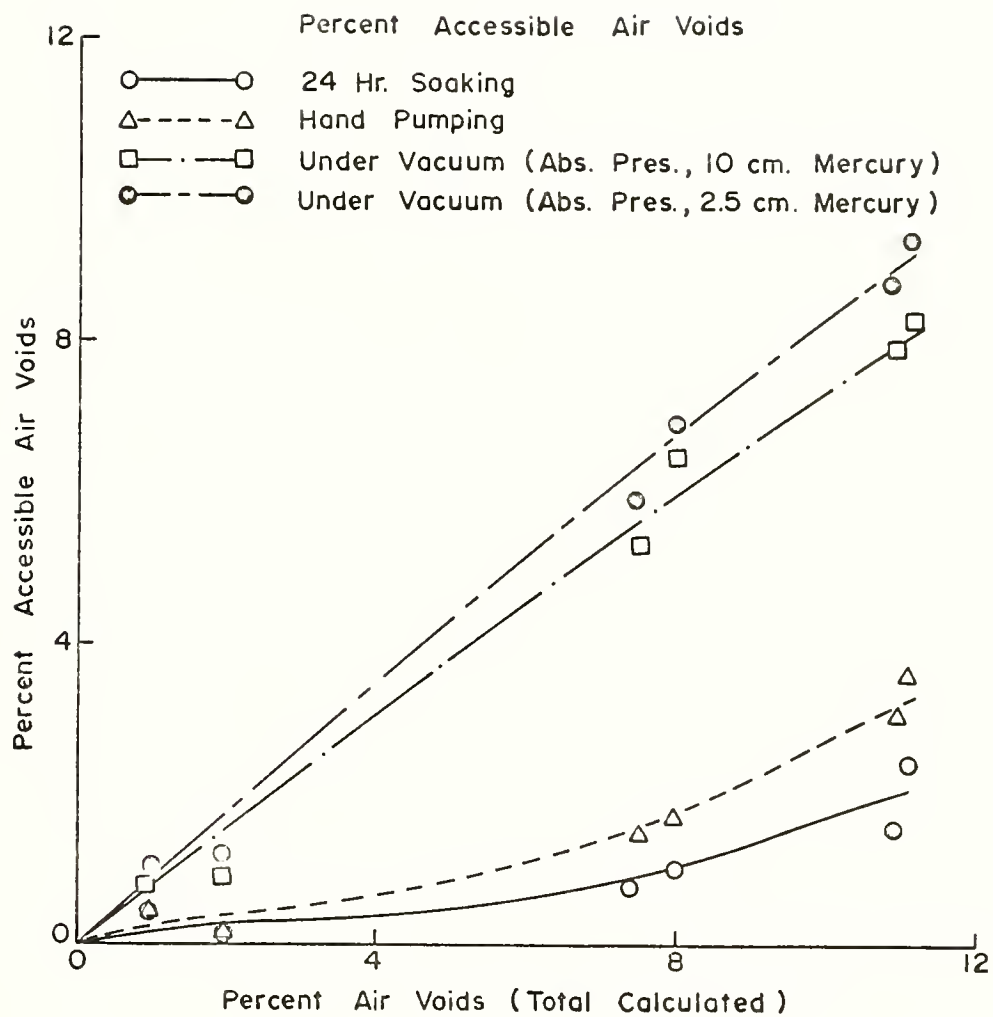


FIGURE 12 - PERCENT ACCESSIBLE AIR VOIDS VS PERCENT AIR VOIDS (TOTAL CALCULATED) FOR GRADED MIXTURES (GROUP C)

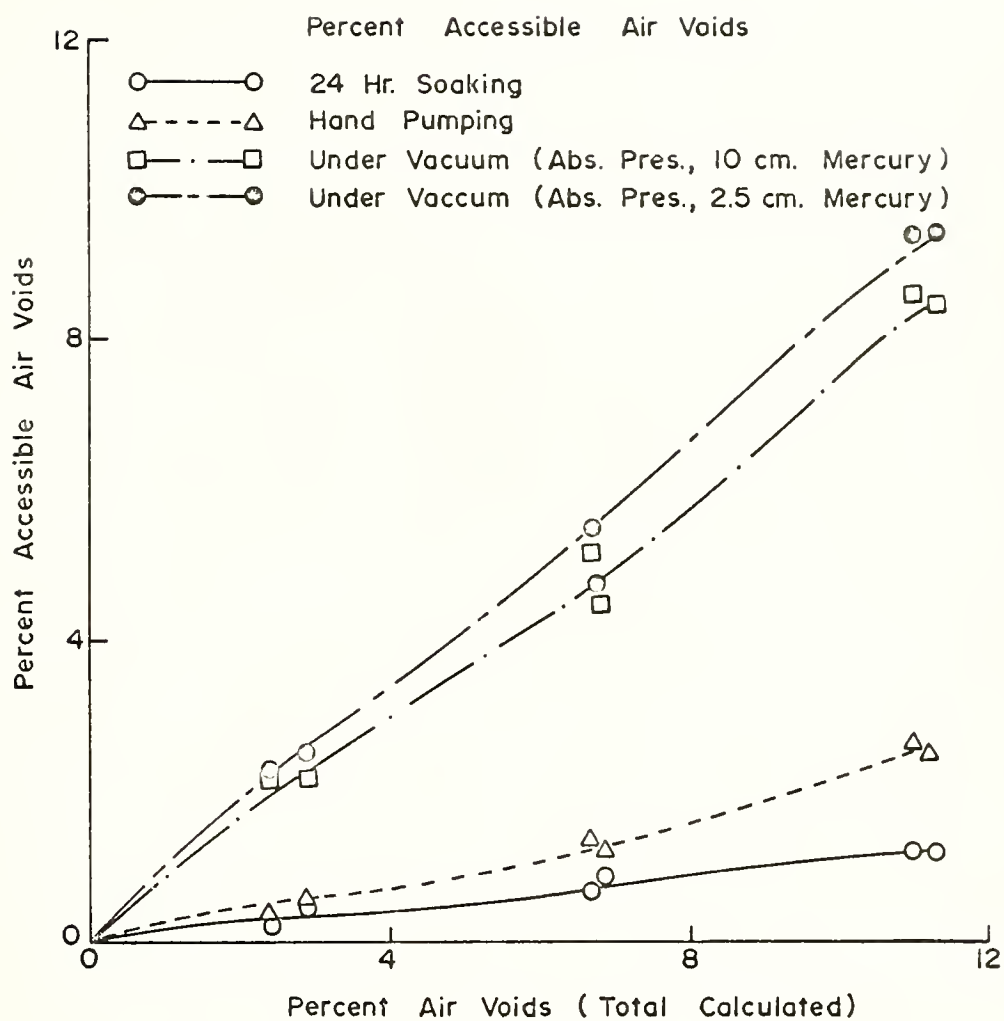


FIGURE 13 - PERCENT ACCESSIBLE AIR VOIDS VS PERCENT AIR VOIDS (TOTAL CALCULATED) FOR GRADED MIXTURES (GROUP A)

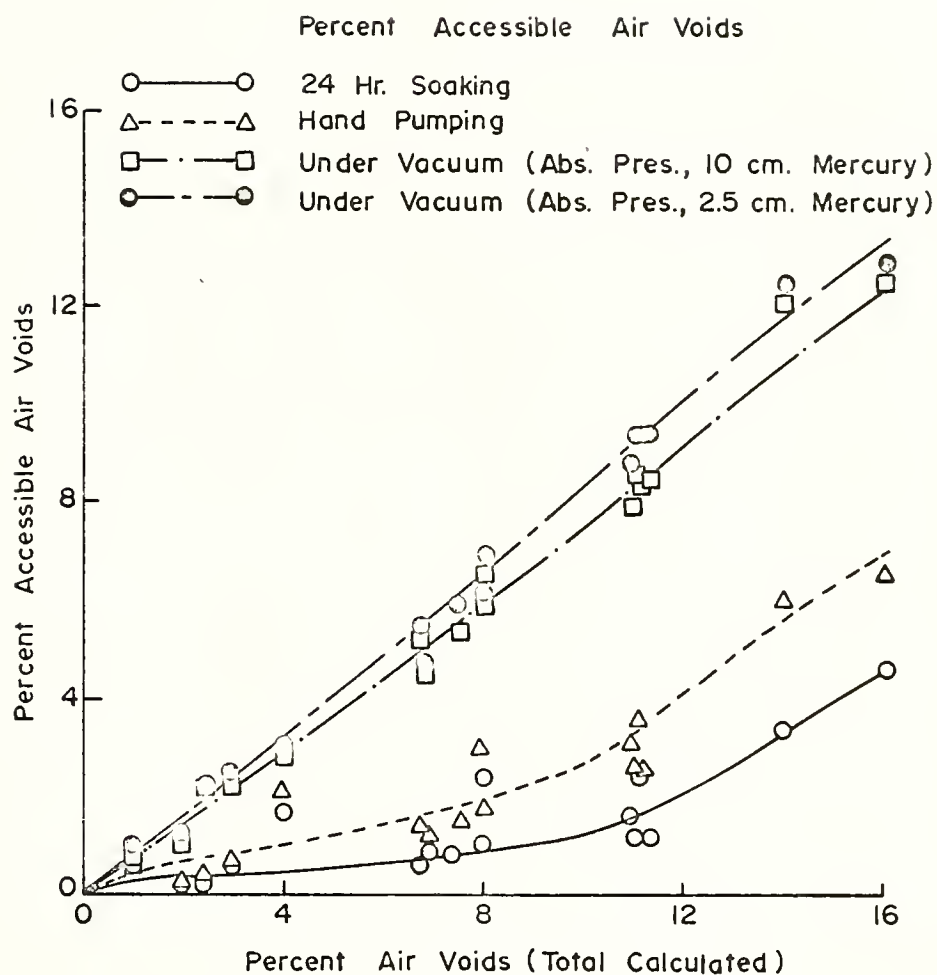


FIGURE 14 - PERCENT ACCESSIBLE AIR VOIDS VS PERCENT AIR VOIDS (TOTAL CALCULATED) FOR GRADED MIXTURES (GROUPS G, C AND A)

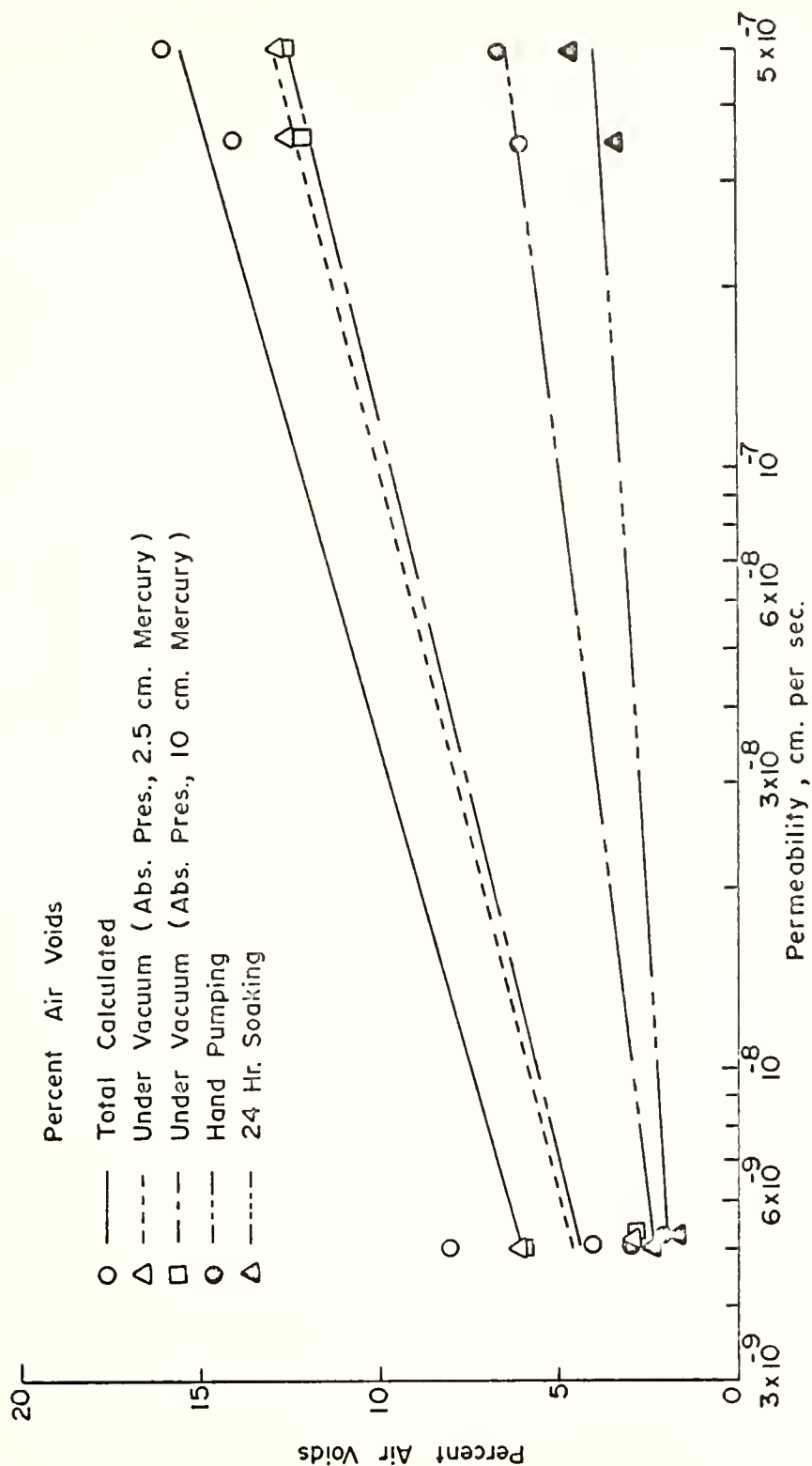


FIGURE 15 - PERCENT AIR VOIDS VS PERMEABILITY FOR GRADED MIXTURES (GROUP G)

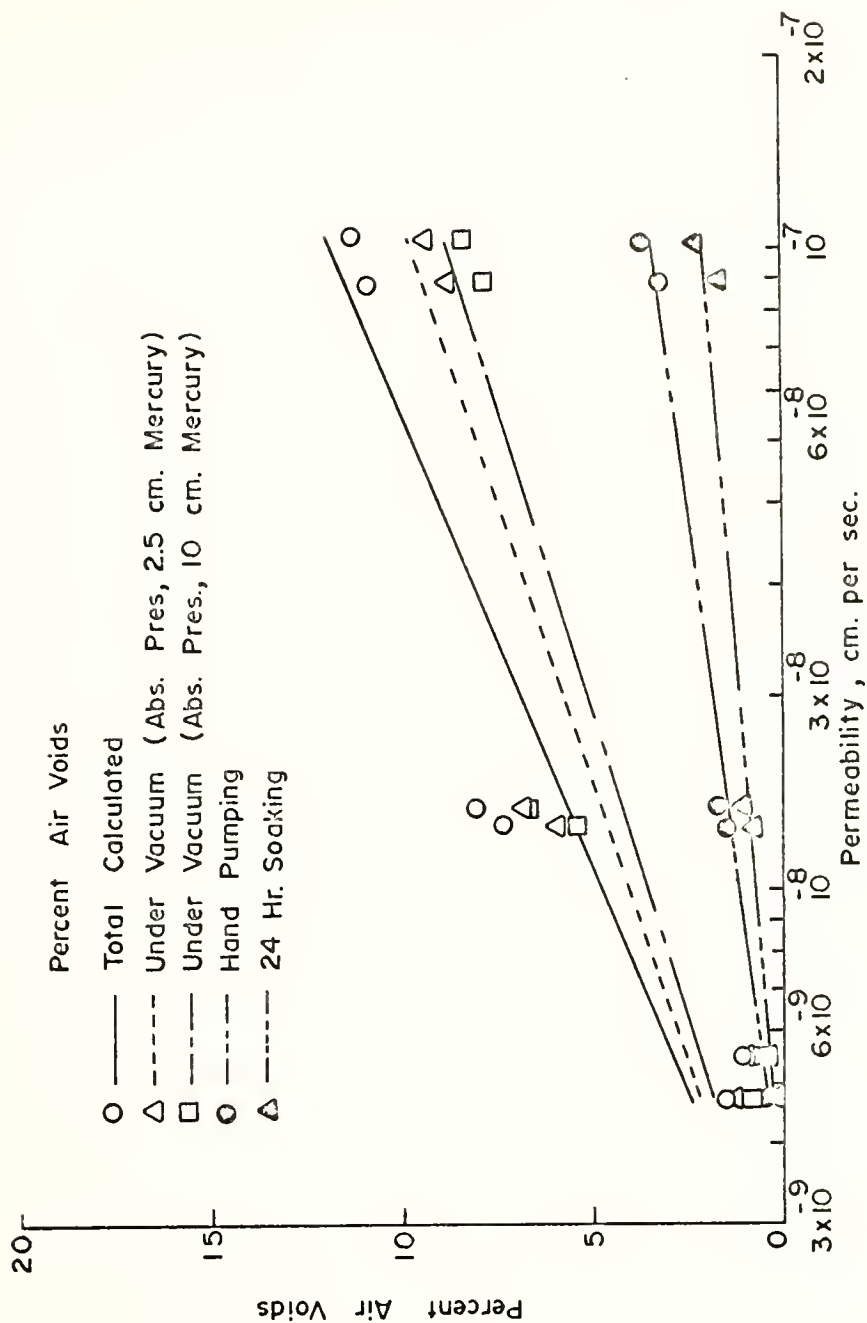


FIGURE 16 - PERCENT AIR VOIDS VS PERMEABILITY FOR GRADED MIXTURES (GROUP C)

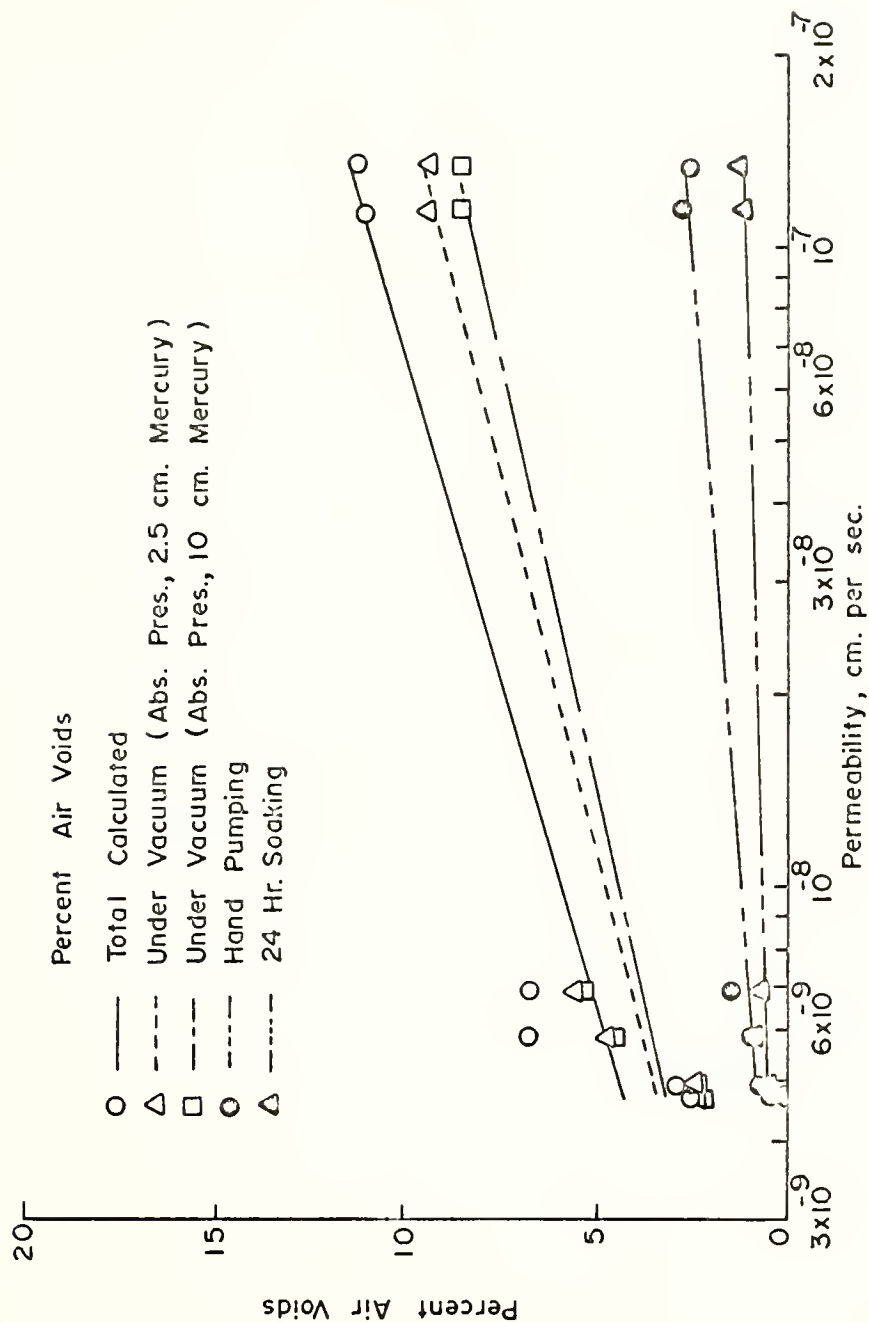


FIGURE 17 - PERCENT AIR VOIDS VS PERMEABILITY FOR GRADED MIXTURES (GROUP A)

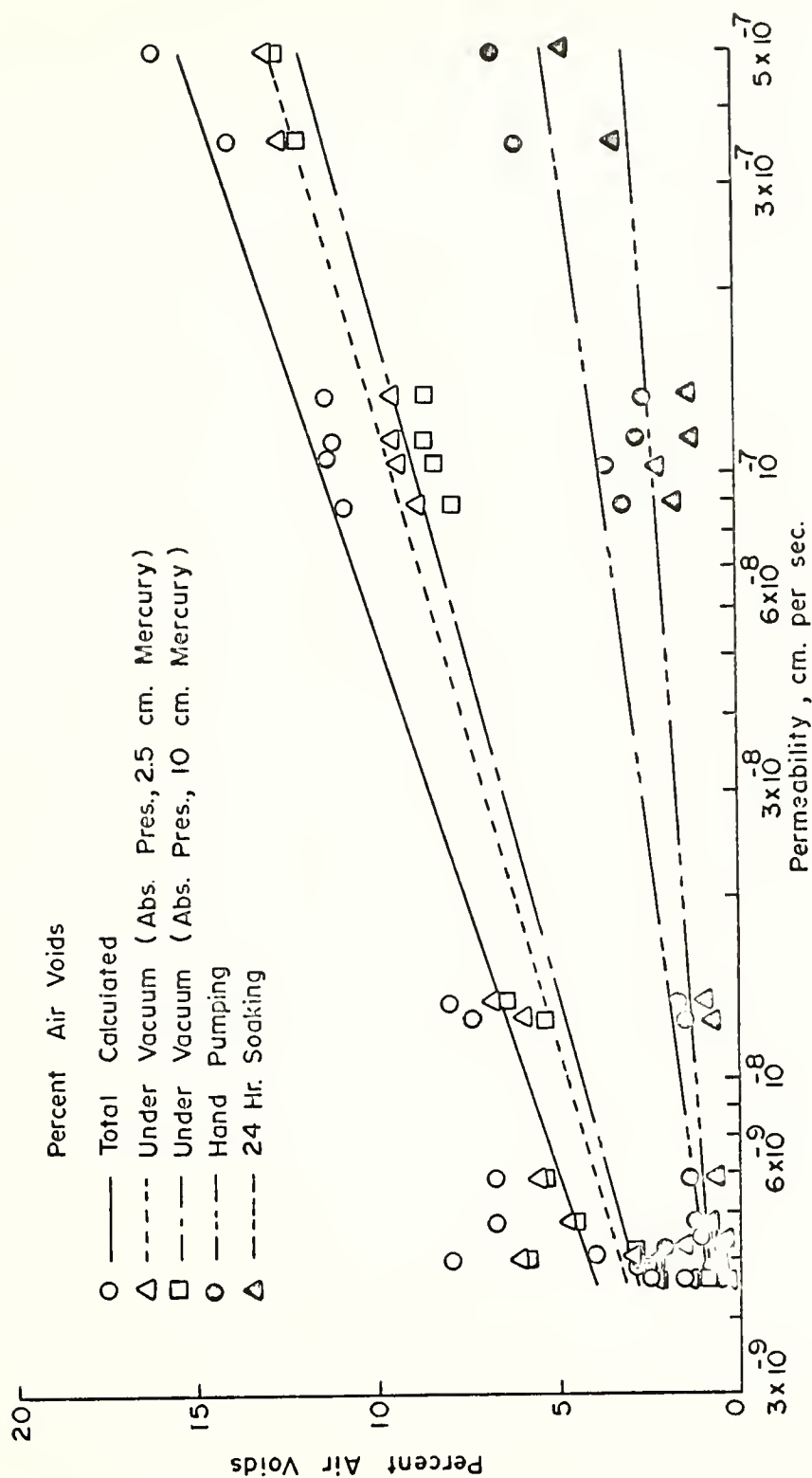


FIGURE 18 - PERCENT AIR VOIDS VS PERMEABILITY FOR GRADED MIXTURES
(GROUPS G, C AND A)

Table 35. Slope, R^2 and Z Values for the Straight Line Plots Between Percent Air Voids and Permeability for Graded Mixtures (Groups G, C and A)

Percent Air Voids	Slope					R^2			Z		
	Gr.G	Gr.C	Gr.A	All	Gr.G	Gr.C	Gr.A	All	Gr.G	Gr.C	Gr.A
Total calculated	4.704	7.027	4.957	5.496	.902	.854	.833	.838	1.8318	1.6157	1.5453
Accessible, Under Vacuum (Abs. Pres., 2.5 cm Hg)	4.203	5.735	4.300	4.715	.930	.848	.905	.876	1.9996	1.5956	1.8421
Accessible, Under Vacuum (Abs. Pres., 10 cm Hg)	4.076	5.194	3.836	4.454	.935	.821	.883	.856	2.0439	1.5047	1.7380
Accessible (Hand Pumping)	2.007	2.308	1.290	2.153	.981	.980	.898	.751	2.6467	2.6467	1.8117
Accessible (24-Hour Soaking)	1.035	1.306	0.481	1.186	.833	.908	.720	.536	1.5453	1.8635	1.2526

The Analysis of Variance Test was performed on the Z values (Table 35), transformed from R values, and the results are presented in Table 36. It is indicated that there is a significant difference between the void types. The Newman Keuls Sequential Range Test was then conducted on the void types. The results (Table 36) show that percent accessible air voids (hand pumping) is significantly different from the rest of them and is ranked highest in their order of means.

Thus, it can be concluded that percent accessible air voids as determined by hand pumping is most closely related and can be used in lieu of a permeability measurement. Using the above information, a hypothetical model of the air void system in compacted asphaltic mixtures is presented in Figure 19.

Comparison of Recovery and Creep Test Results

After the weathering (oxidation) and creep testing cycles were completed, and void measurements on all the single-size and graded mixture specimens had been made, it was decided to recover the asphalt. The purpose was to compare the recovery and creep test results. However, since considerable time had elapsed after the last creep test, that creep data was not considered to be valid for comparison. Therefore, the creep test was again performed on all the specimens just before asphalt extraction.

In this section the results of the creep tests performed before extraction on all single-size and graded mixtures are presented, and penetration values of the recovered asphalt are given. A comparison is then made between the penetration values of the recovered asphalt

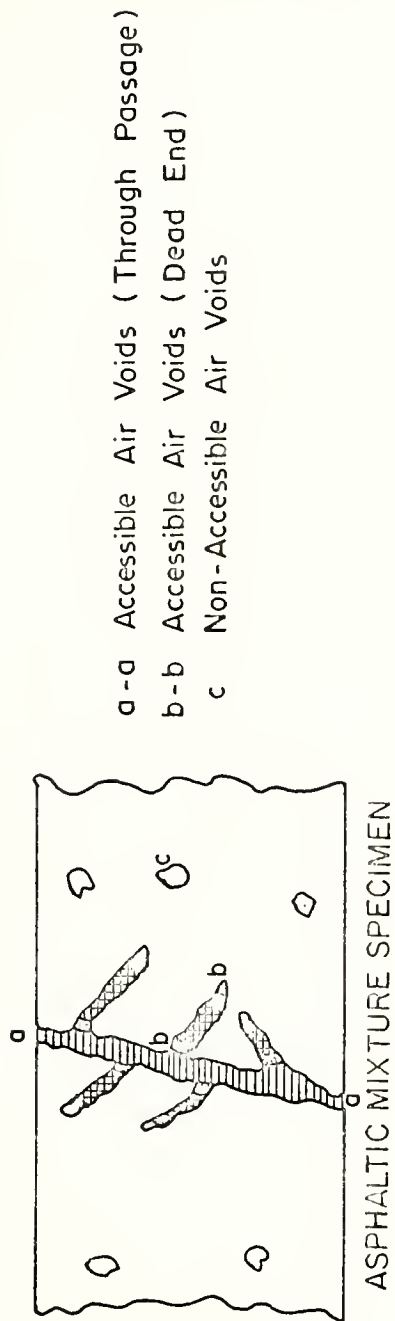
Table 36. Analysis of Variance and Newman Keuls Sequential Range Test Results on Z Values Obtained from Percent Air Voids vs Permeability Plots for Graded Mixtures

<u>ANOVA</u>					
Source	Sum of Squares	Degrees of Freedom	Mean Square	F	F ^(0.05) _{crit}
Mix Type (T)	0.3538	2	0.1769	2.71	4.74
Voids Type (V)	1.1954	4	0.2989	4.58*	4.12
TxV (non-additivity)+	0.1150	1	0.1150	1.76	5.59
Error	0.4565	7	0.0652		

<u>NKSRT</u>		
Rank	Ranked Order of Means	Ranked Means
1	Percent Accessible Air Voids (Hand Pumping)	2.3684
2	Percent Accessible Air Voids Under Vacuum (Abs. Pres., 2.5 cm Mercury)	1.8124
3	Percent Accessible Air Voids Under Vacuum (Abs. Pres., 10 cm Mercury)	1.7622
4	Percent Air Voids (Total Calculated)	1.6643
5	Percent Accessible Air Voids (24-Hour Soaking)	1.5538

<u>Table of Differences Between Means</u>				
Rank	5	4	3	2
1	.815*	.704*	.606*	.556*
2	.259	.148	.050	
3	.208	.098		
4	.111			

* Significant at 5 percent level.
 + Reference No. 28.



- a-a Accessible Air Voids (Through Passage)
- b-b Accessible Air Voids (Dead End)
- c Non-Accessible Air Voids

<u>WATER SATURATION TECHNIQUE</u>		<u>VOIDS FILLED</u>
24 HOUR SOAKING		
24 HOUR SOAKING + HAND PUMPING		
VACUUM (Abs. Pres., 10 cm. Mercury)		
VACUUM (Abs. Pres., 2.5 cm. Mercury)		

FIGURE 19 - AIR VOID SYSTEM IN COMPACTED ASPHALTIC MIXTURES (HYPOTHETICAL MODEL)

after weathering and the results of the creep test conducted on the specimens just before they were subjected to asphalt recovery.

The creep test was carried out on all the specimens of single-size and graded mixtures except specimens no. A1 and A2 of the graded mixture (Group A). The reason for rejection of those two specimens was that, in comparison to the others in the group, appreciable asphalt hardening had occurred during mixing. This is explained in detail in the section 'Application of Durability Evaluation'. The creep test results are presented in Table 37 and Figures 20 and 21.

After the creep test, the silicone coating was peeled off the specimen (Figure 5), and the asphalt was extracted (ASTM: D 2172) and then recovered using the Abson Recovery (ASTM: D 1856) procedure. The penetration test (ASTM: D 5) was then carried out on the recovered asphalt. The penetration values of the asphalts recovered from the individual specimens of both single-size and graded mixtures are presented in Table 38.

It was indicated earlier in the section 'Creep Curve Interpretation', that the ratio of the creep curve slope (or intercept) at 'X' days weathering (oxidation) to creep curve slope (or intercept) at no weathering (oxidation), gives a measure of asphalt hardening in asphaltic mixtures. This ratio was referred to as durability index (slope or intercept). The results in the section 'Single-Size Mixtures' indicated that the durability index (slope) is more sensitive to asphalt hardening in comparison to the durability index (intercept), and so is a better predictor of durability. Therefore, in this section a comparison is made between the durability index (slope) and the

Table 37. Strain vs Time for Single-Size and Graded Mixtures Tested Before Extraction

Strain, in/in x 10 ⁻⁵										
Time in Secs.	Single-Size Mixtures						Graded Mixtures (Group G)			
	Specimen No.						Specimen No.			
	S1	S2	S3	S4	S5	S6	G1	G2	G3	G4
10	27.04	26.92	17.10	28.26	10.66	23.20	13.87	17.43	19.75	17.45
30	32.06	32.10	21.03	33.30	17.42	28.09	17.46	21.63	23.81	20.74
60	35.49	35.30	23.57	37.40	19.49	31.59	20.77	24.90	27.31	23.45
120	39.16	39.26	26.46	41.49	22.89	36.02	24.91	29.79	32.21	26.88
180	41.48	41.58	28.31	44.29	24.60	38.70	27.82	33.46	35.85	28.46
300	44.67	44.65	30.62	48.38	27.15	42.89	32.65	39.18	41.04	31.89

Graded Mixtures (Group C)										
Specimen No.										
C1	C2	C3	C4	C5	C6	A3	A4	A5	A6	
10	18.51	21.80	17.70	19.79	12.47	13.37	17.58	16.73	21.44	22.30
30	22.76	26.22	22.32	23.35	14.26	15.97	22.36	20.57	25.57	26.12
60	26.33	29.81	25.85	26.37	16.32	17.73	24.82	23.03	28.32	28.85
120	30.30	34.36	31.44	30.22	18.37	19.51	28.81	26.59	32.44	32.67
180	33.32	37.54	33.05	32.54	19.61	20.61	31.00	29.06	35.05	35.12
300	37.71	42.24	37.80	35.97	21.94	22.65	35.40	33.03	39.04	39.08

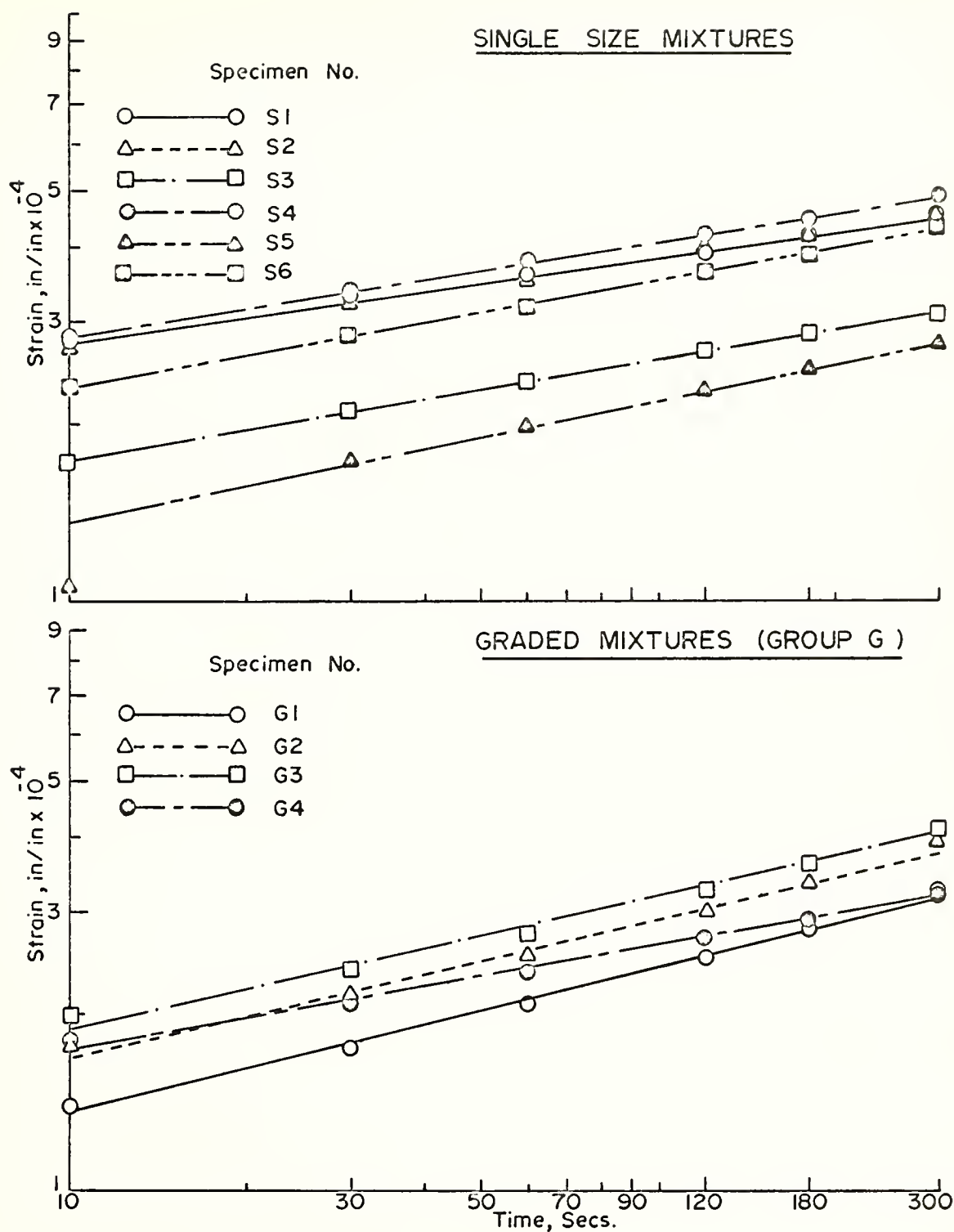


FIGURE 20 - STRAIN VS TIME FOR SINGLE-SIZE AND GRADED (GROUP G) MIXTURES TESTED BEFORE EXTRACTION

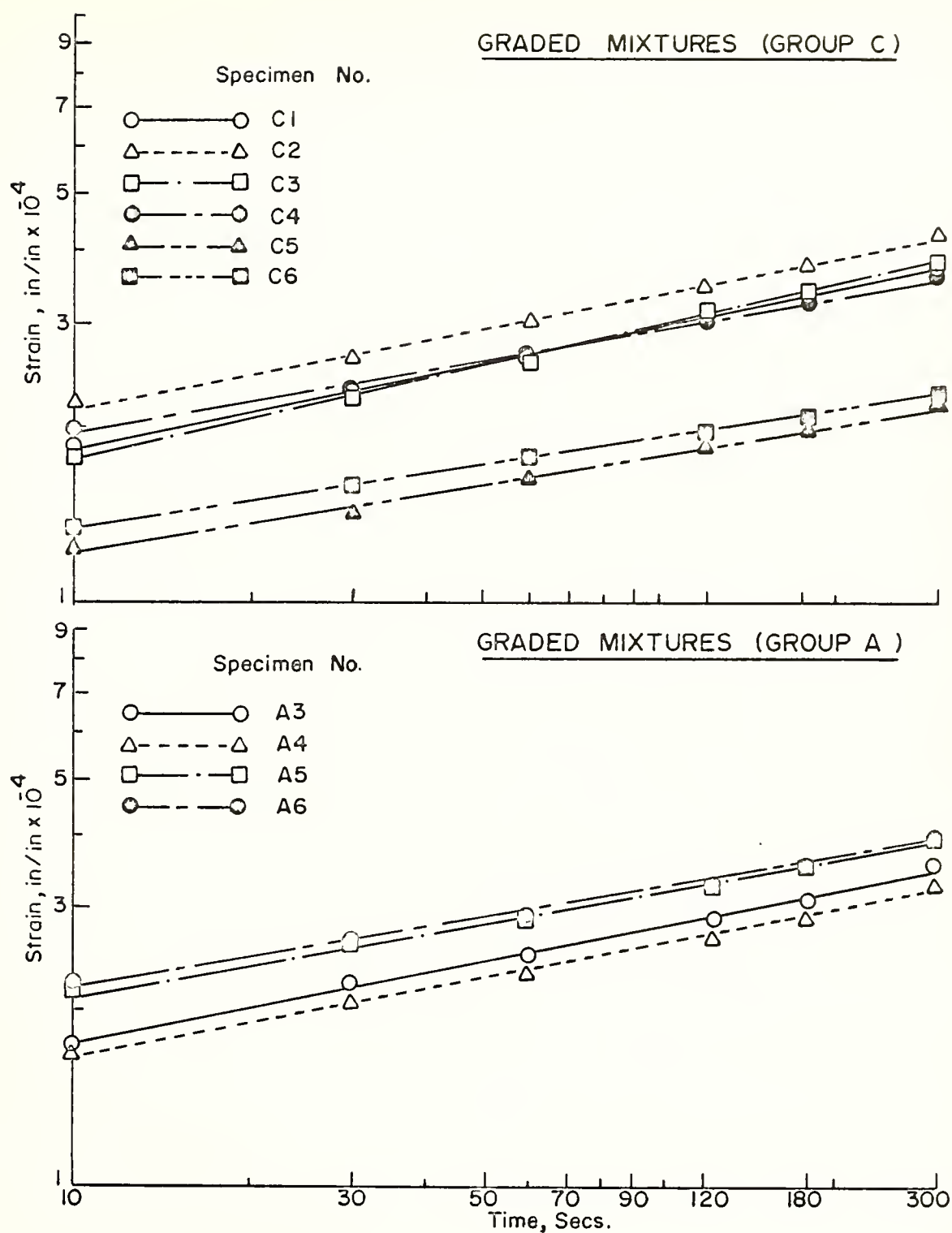


FIGURE 21 - STRAIN VS TIME FOR GRADED MIXTURES (GROUPS C AND A) TESTED BEFORE EXTRACTION

penetration values. The creep curve slope values and the durability index (slope) values for the specimens before extraction are presented in Table 38.

According to the author's interpretation, (refer to section 'Creep Curve Interpretation') a higher value of durability index (slope) indicates more asphalt hardening. Therefore, for higher values of durability index (slope), the recovered asphalt should have a lower penetration value. If this were true, then it would be right to conclude that durability index (slope) is a measure of asphalt hardening in asphaltic mixtures.

Keeping the above logic in mind, the results for single-size and graded mixtures are now discussed. Plots made between the durability index (slope) and the days of weathering for both single-size and graded mixtures are presented in Figures 22 to 25. It may be noted that the term 'weathering' in these Figures refers to oxidation caused by passing air through the specimens kept in the oven at 140F(60C). (See section 'Oxidation of Compacted Asphaltic Mixture Specimens'.) The term 'laboratory aging' refers to the hardening that may have occurred during the time between the last day of oxidation in the oven and the time of asphalt extraction. During this period the specimens were stored on shelves in the laboratory at room temperature (70 to 75F; 21.1 to 23.9C).

The results for single-size and graded mixtures are analyzed as follows:

Single-Size Mixtures: The plot (Figure 22) for single-size mixtures indicates that at the end of laboratory aging specimen

Table 38. Asphalt Penetration Values of the Recovered Asphalt and Creep Curve Slope Values Before Extraction of Single-Size and Graded Mixtures

Mixture Type	Specimen No.	Creep Curve Slope Before Extraction	Durability Index (Slope) Before Extraction	Asphalt Penetration* After Absorption Recovery
Single Size	S1	0.147	2.162	75
	S2	0.149	2.094	76
	S3	0.172	2.298	72
	S4	0.158	2.256	73
	S5	0.263	3.984	61
	S6	0.179	2.522	69
Graded (Group G)	G1	0.251	4.276	51
	G2	0.236	3.684	55
	G3	0.215	3.335	72
	G4	0.177	2.794	91
Graded (Group C)	C1	0.208	2.966	74
	C2	0.194	2.361	73
	C3	0.224	2.696	75
	C4	0.177	2.075	81
	C5	0.166	1.674	109
	C6	0.152	2.120	107
Graded (Group A)	A3	0.200	2.675	79
	A4	0.196	2.898	80
	A5	0.175	2.627	112
	A6	0.164	2.250	113

* @ 100 grams, 5 sec., 77F (25C)

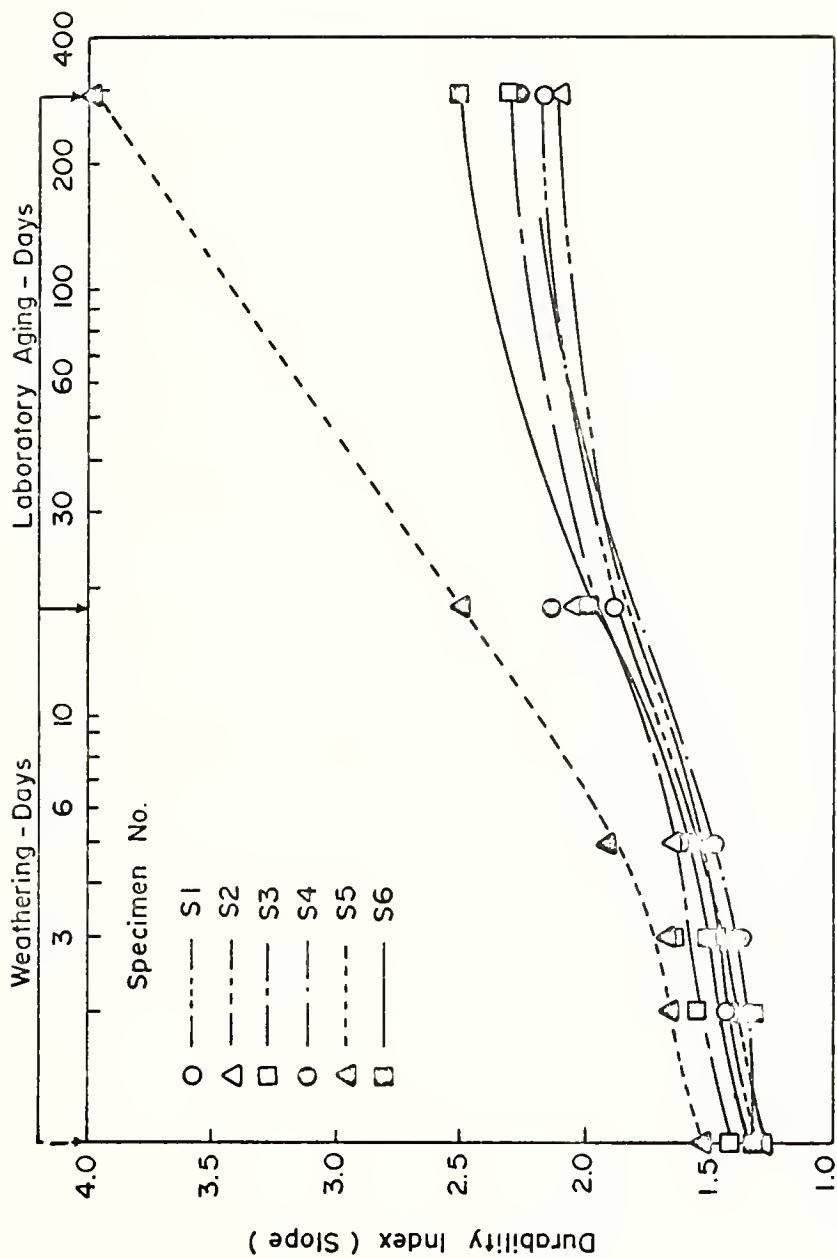


FIGURE 22 - DURABILITY INDEX (SLOPE) VS WEATHERING FOR SINGLE-SIZE MIXTURES

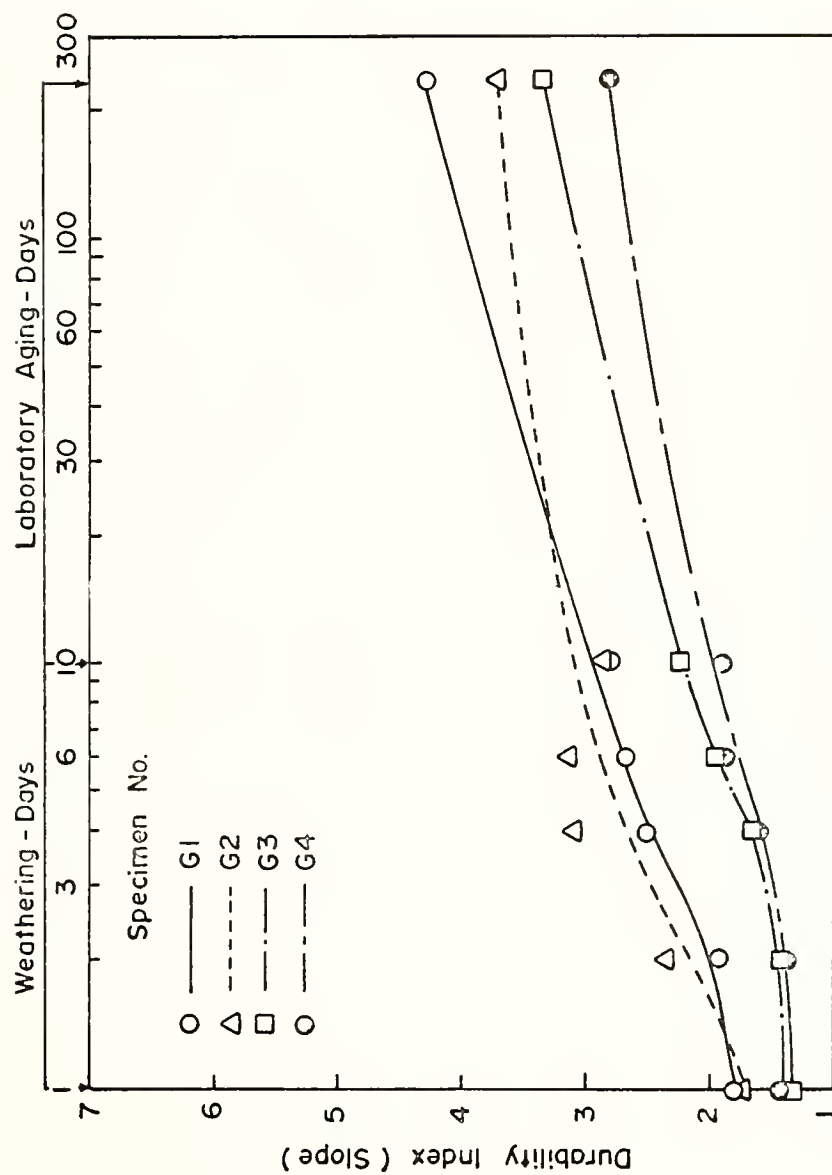


FIGURE 23 - DURABILITY INDEX (SLOPE) VS WEATHERING FOR GRADED MIXTURES (GROUP G)

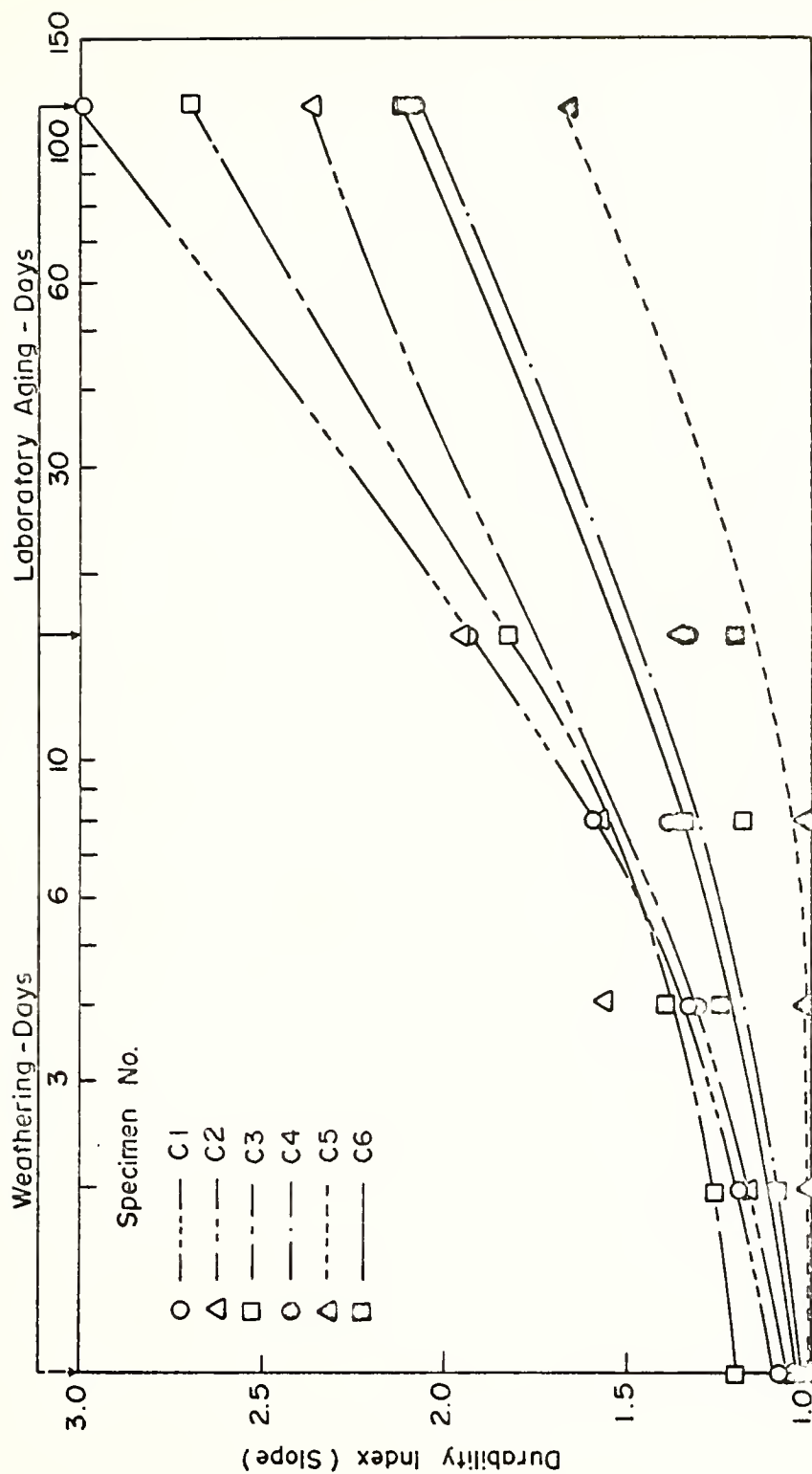


FIGURE 24 - DURABILITY INDEX (SLOPE) VS WEATHERING FOR GRADED MIXTURES (GROUP C)

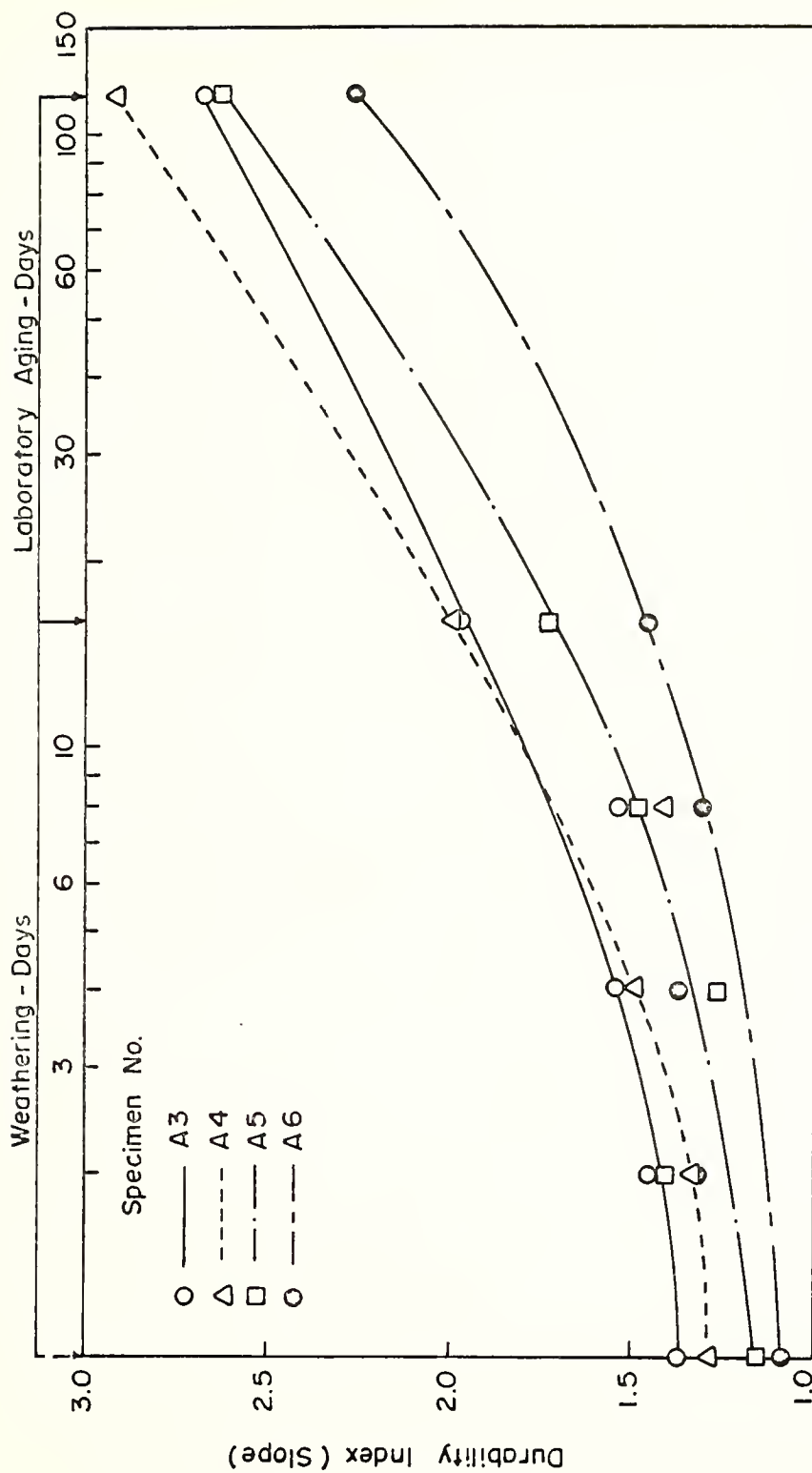


FIGURE 25 - DURABILITY INDEX (SLOPE) VS WEATHERING FOR GRADED MIXTURES (GROUP A)

no. S5 had weathered the most while specimen no. S6 was next in order. Specimens no. S1 and S2 weathered the least since they have the lowest durability index (slope) values. On examining the penetration values of the recovered asphalt (Table 38), it was observed that specimen no. S5 had the lowest value, and specimen no. S6 had the next lowest value. Specimens no. S1 and S2 had comparatively high penetration values, indicating comparatively less weathering.

Graded Mixture (Group G): Figure 23 shows that at the end of the laboratory aging period, specimen no. G1 had the highest durability index (slope) value, followed by nos. G2, G3 and G4 in descending order. Correspondingly, the penetration values (Table 38) in increasing order relate to specimens nos. G1, G2, G3 and G4.

Graded Mixture (Group C): The penetration data (Table 38) indicate that specimens no. C5 and C6 have the highest values. Specimens no. C1, C2 and C3 have almost the same penetration values and are at the lower end of the scale, with specimen no. C4 falling in between. Looking at Figure 24 it appears that the three specimens (nos. C1, C2 and C3) have high durability index (slope) values at the end of the laboratory aging period. However, they seem to be separated more than the penetration results suggest. Specimen no. C5 had the lowest durability index (slope) value and the highest penetration value. Specimens no. C4 and C6 have nearly equal durability index (slope) values (Figure 24), whereas their penetration values are somewhat different.

Graded Mixture (Group A): According to Figure 25, specimen no. A4 has the highest value of durability index (slope) at the end of

laboratory aging, and specimen no. A6 has the lowest value. Specimens no. A3 and A5 fall in between with values rather close to each other. The penetration results (Table 38) indicate that specimen no. A4 has almost the lowest value while specimen no. A6 has the highest value. Specimens no. A3 and A5 have values close to those of specimens no. A4 and A6 respectively.

The above discussion indicates that, in general, it can be concluded that durability index (slope) is a measure of asphalt hardening in asphaltic mixtures. The reason for some discrepancy in the correlation between asphalt hardening as measured by slope of the creep curve and as measured by penetration of recovered asphalt could be due to the fact that the penetration value of the recovered asphalt is an average value for the asphalt in the asphaltic mixture whereas the creep test value may be a better measure of the effect of asphalt hardening.

Application of Durability Evaluation

In this section the feasibility of using the accelerated oxidation and creep testing procedure for asphaltic mixture evaluation in terms of resistance to asphalt hardening is examined.

In order to study the applicability of the test procedure, two groups of specimens were formed. In one group (Group C) the mixture composition was kept constant and specimens were prepared at different compactive efforts; in the other group (Group A) specimens were prepared with asphalt content as the variable. The specimens were then subjected to repeated cycles of accelerated oxidation and creep testing (details are presented in sections 'Materials and Specimen Preparation' and

'Test Procedure'). The analyses of the results for the two groups, varying compactive effort and varying asphalt content, are presented in the following sections.

Varying Compactive Effort Group (Group C): Duplicate specimens were prepared using three levels of compactive effort; low, medium and high corresponding to about 11, 7.5 and 1 percent total air voids, respectively (Table 7). All the specimens had the same asphalt content and almost the same height. Under these conditions any variations in asphalt hardening (as recorded by creep tests) that occurred between specimens during the process of accelerated oxidation should be due mainly to variations in compactive effort. For low compactive effort there should be more hardening, and for high compactive effort the asphalt hardening should be comparatively less.

In order to study the comparative levels of asphalt hardening among the specimens (nos. C1 to C6), least square plots were made between durability index (slope) and days of weathering (oxidation) (Figure 26) and between durability index (intercept) and days of weathering (oxidation) (Figure 27). Linear regression analyses were performed for all the six specimens and their slope values are presented in Table 39. The results indicate that specimens made with low compactive effort (nos. C1 and C2) have high slope values (more asphalt hardening) and the ones made with high compactive effort (nos. C5 and C6) have low slope values (less asphalt hardening). The slope values for the specimens made with medium compactive effort (nos. C3 and C4) lie in between the two extremes. The results are similar for both durability index (slope) and durability index (intercept). A higher value of slope means more

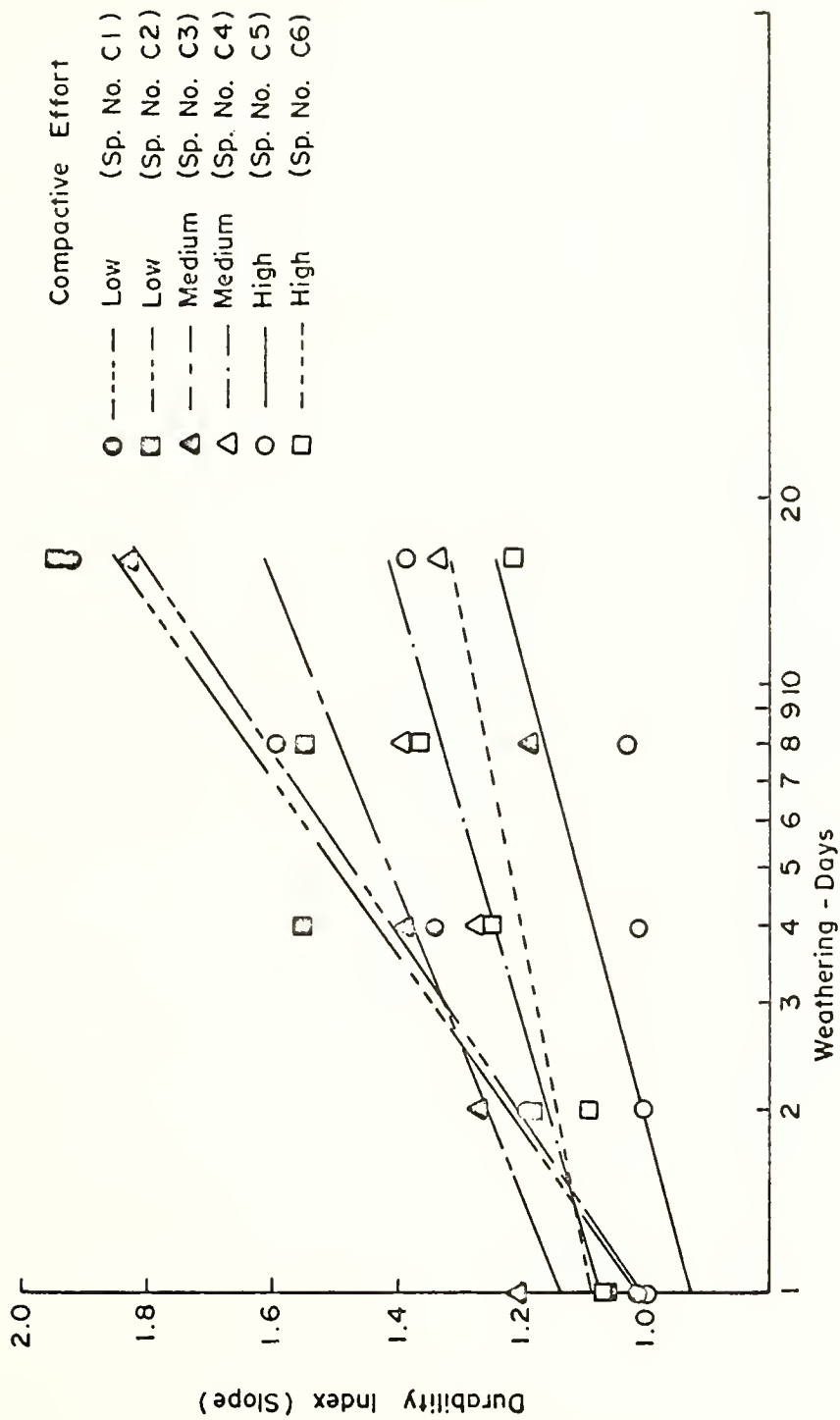


FIGURE 26 - DURABILITY INDEX (SLOPE) VS WEATHERING (OXIDATION) FOR SPECIMENS MADE WITH VARYING COMPACTIVE EFFORT (GRADED MIXTURE, GROUP C)

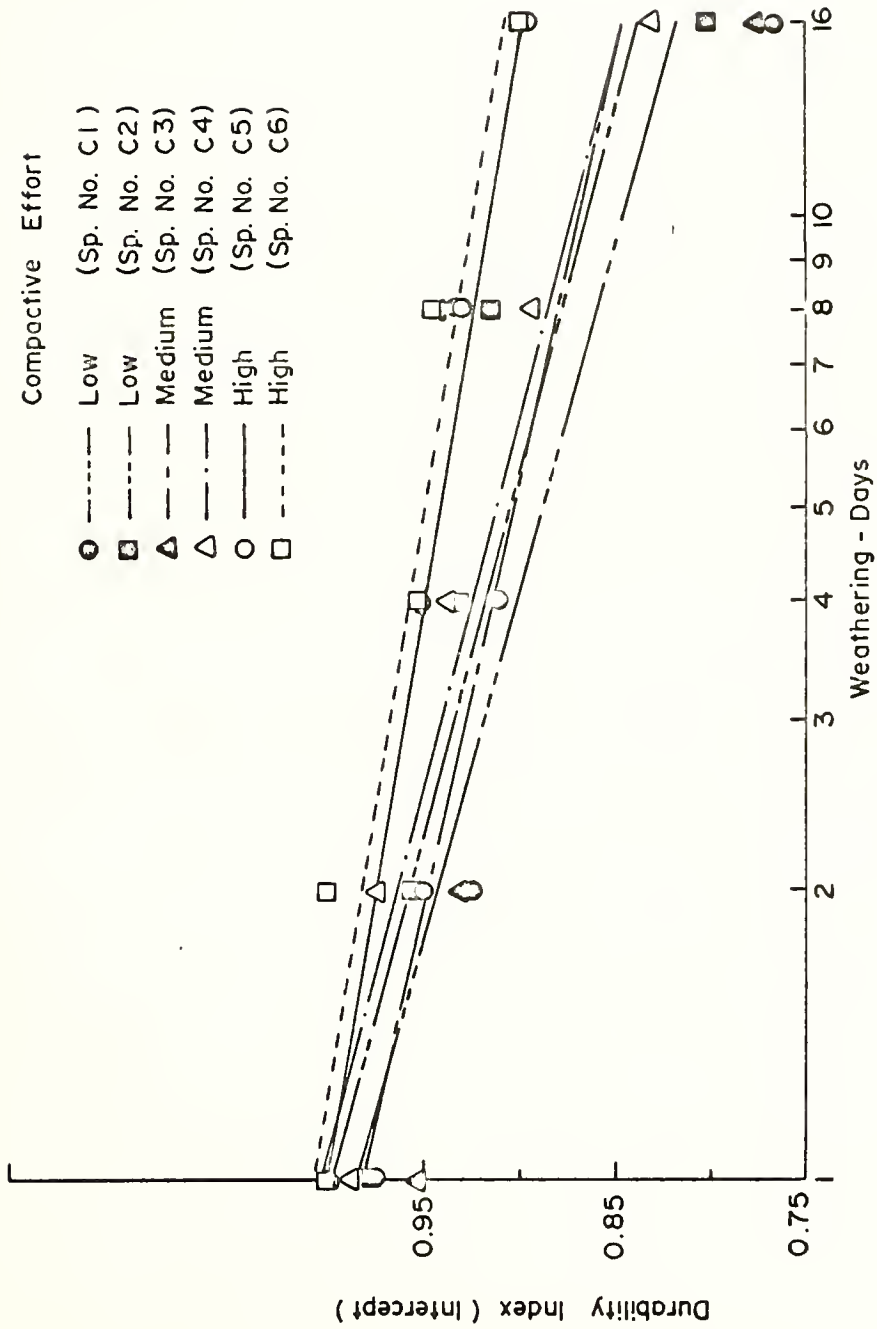


FIGURE 27 - DURABILITY INDEX (INTERCEPT) VS WEATHERING (OXIDATION) FOR SPECIMENS MADE WITH VARYING COMPACTIVE EFFORT (GRADED MIXTURE, GROUP C)

Table 39. Slopes of the Straight Line Plots Between Durability Index and Weathering (Oxidation) for Specimens with Varying Compactive Effort (Group C)

For Durability Index (Slope)

Compactive Effort								
Low			Medium			High		
Specimen No.	Slope	Ave.	Specimen No.	Slope	Ave.	Specimen No.	Slope	Ave.
C1	.691	.682	C3	.390	.335	C5	.262	.224
C2	.673		C4	.280		C6	.185	

For Durability Index (Intercept)

Compactive Effort								
Low			Medium			High		
Specimen No.	Slope	Ave.	Specimen No.	Slope	Ave.	Specimen No.	Slope	Ave.
C1	-.139	-.136	C3	-.115	-.123	C5	-.077	-.083
C2	-.132		C4	-.131		C6	-.088	

weathering (that is more asphalt hardening), and a lower slope value corresponds to less asphalt hardening.

The results were statistically analyzed in order to find if there existed any significant differences among the three levels of compactive effort. Analysis of Variance Tests were conducted on both the durability index (slope) and the durability index (intercept) values. The results, presented in Tables 40 and 41, show that there is a significant difference (5 percent level) among the three levels of compactive effort in both cases (slope and intercept). The Newman Keuls Sequential Range Test was now performed for the three levels of compactive effort. The results are presented in Tables 40 and 41 and Figure 28.

According to the analysis based on durability index (slope) (Figure 28), all the three levels (low, medium and high) are significantly different from each other at the 10 percent statistical level. The low and the medium compactive effort levels do not show any significant difference between each other at the 5 percent statistical level, but both are significantly different to the high compactive effort level.

The analysis based on the intercepts of the creep curves (Figure 28) indicates that there is no significant difference between the low and the medium compactive effort levels at both the 5 percent and 10 percent statistical levels, but they are both significantly different to the high compactive effort level.

Table 40. Analysis of Variance (ANOVA) and Newman-Keuls Sequential Range Test Results (NKSRT) for Durability Index (Slope) Values of the Mixtures with Varying Compactive Effort (Group C)

<u>ANOVA</u>				
Source	Sum of Squares	Degrees of Freedom	Mean Square	F
Compactive Effort (C)	.4466	2	.2233	11.15*
Oxidation-Days (O)	1.0200	4	.2550	12.73*
Interaction (CxO)	.2488	8	.0311	1.55
Pooled Error	.3000	15	.0200	

NKSRT

<u>Compactive Effort</u>		<u>Table of Differences Between Means</u>		
Ranked Order of Means	Ranked Means	Rank	2	3
1 Low	1.440	1	.298**	.133*
2 Medium	1.307	2	.165**	
3 High	1.142			

* Significant at 10 percent level.

** Significant at 5 percent level.

Table 41. Analysis of Variance (ANOVA) and Newman-Keuls Sequential Range Test Results (NKSRT) for Durability Index (Intercept) Values of the Mixtures with Varying Compactive Effort (Group C)

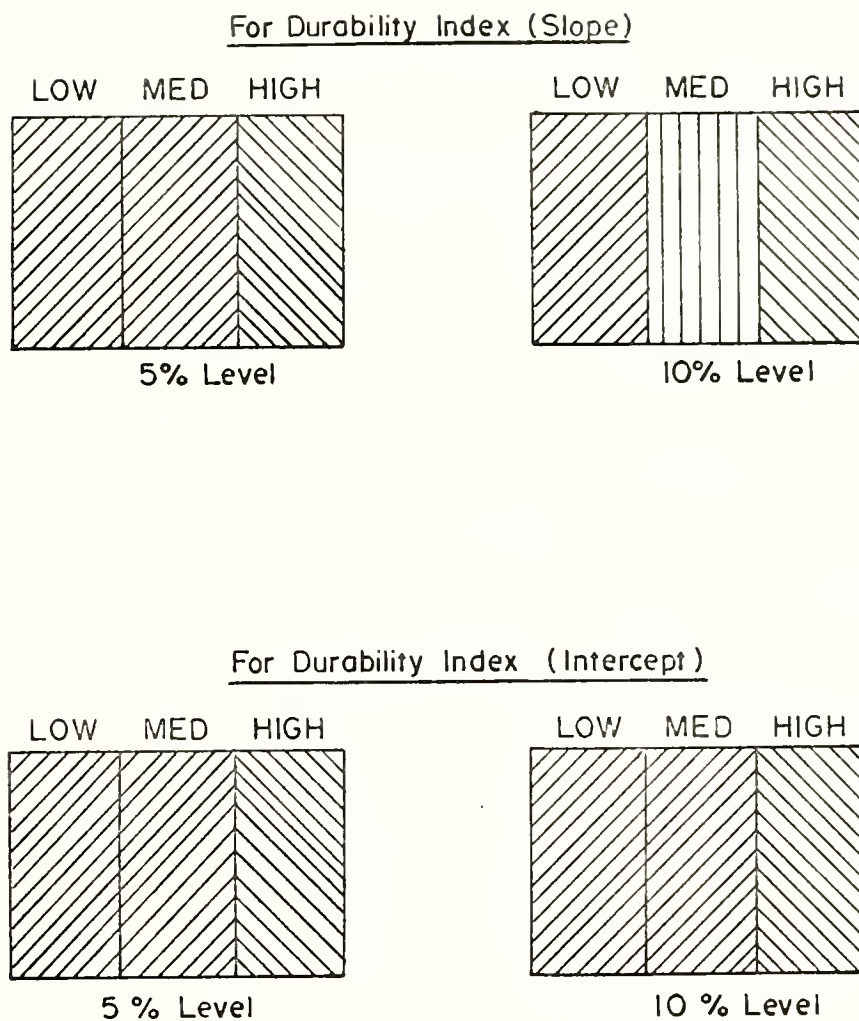
<u>ANOVA</u>				
Source	Sum of Squares	Degrees of Freedom	Mean Square	F
Compactive Effort (C)	.010580	2	.005290	10.73*
Oxidation-Days (O)	.085640	4	.021410	43.43*
Interaction (CxO)	.007504	8	.000938	1.90
Pooled Error	.007395	15	.000493	

NKSRT

<u>Compactive Effort</u>		<u>Table of Differences Between Means</u>		
Ranked Order of Means	Ranked Means	Rank	2	3
1 High	.952	1	.044**	.036**
2 Medium	.916	2	.008	
3 Low	.908			

* Significant at 10 percent level.

** Significant at 5 percent level.



NOTE Difference in values between specimens incorporating different symbols are significant at the specified level

FIGURE 28 - NEWMAN KEULS SEQUENTIAL RANGE TEST RESULTS FOR SPECIMENS MADE WITH VARYING COMPACTIVE EFFORT (GRADED MIXTURE, GROUP C)

The above discussion indicates that the test procedure reflects the resistance to asphalt hardening that may be expected due to compacting the mixture to varying levels of density.

Varying Asphalt Content Group (Group A): Three levels of asphalt content, low, medium and high (3.0, 5.5 and 8.0 percent), were selected and duplicate specimens were prepared for each level. Aggregate density was kept the same for all the specimens, and all were nearly the same height. Logically speaking, the asphalt in specimens with 8.0 percent asphalt should harden less in comparison to the specimens with 3.0 percent asphalt (other factors remaining constant).

In order to study the variations in asphalt hardening in these six specimens (nos. A1 to A6), least square plots were made between durability index (slope) and days of weathering (oxidation), Figure 29, and between durability index (intercept) and days of weathering (oxidation), Figure 30. The slope values based on the linear regression analyses performed on all the six specimens are presented in Table 42. For low, medium and high asphalt content, the slope values should be high, medium and low, respectively. The results are not in line with the above statement for the specimens with low asphalt content. They show a low slope value for low asphalt content specimens (Table 42). It appeared that due to low asphalt content, excess initial hardening during mixing may have occurred. As a result, the creep curve slope at no oxidation may have been considerably higher and the creep curve intercept considerably lower than for higher asphalt content specimens. Durability index (slope) is a ratio of the creep curve slope at 'X' days weathering (oxidation) to the creep curve slope at no weathering

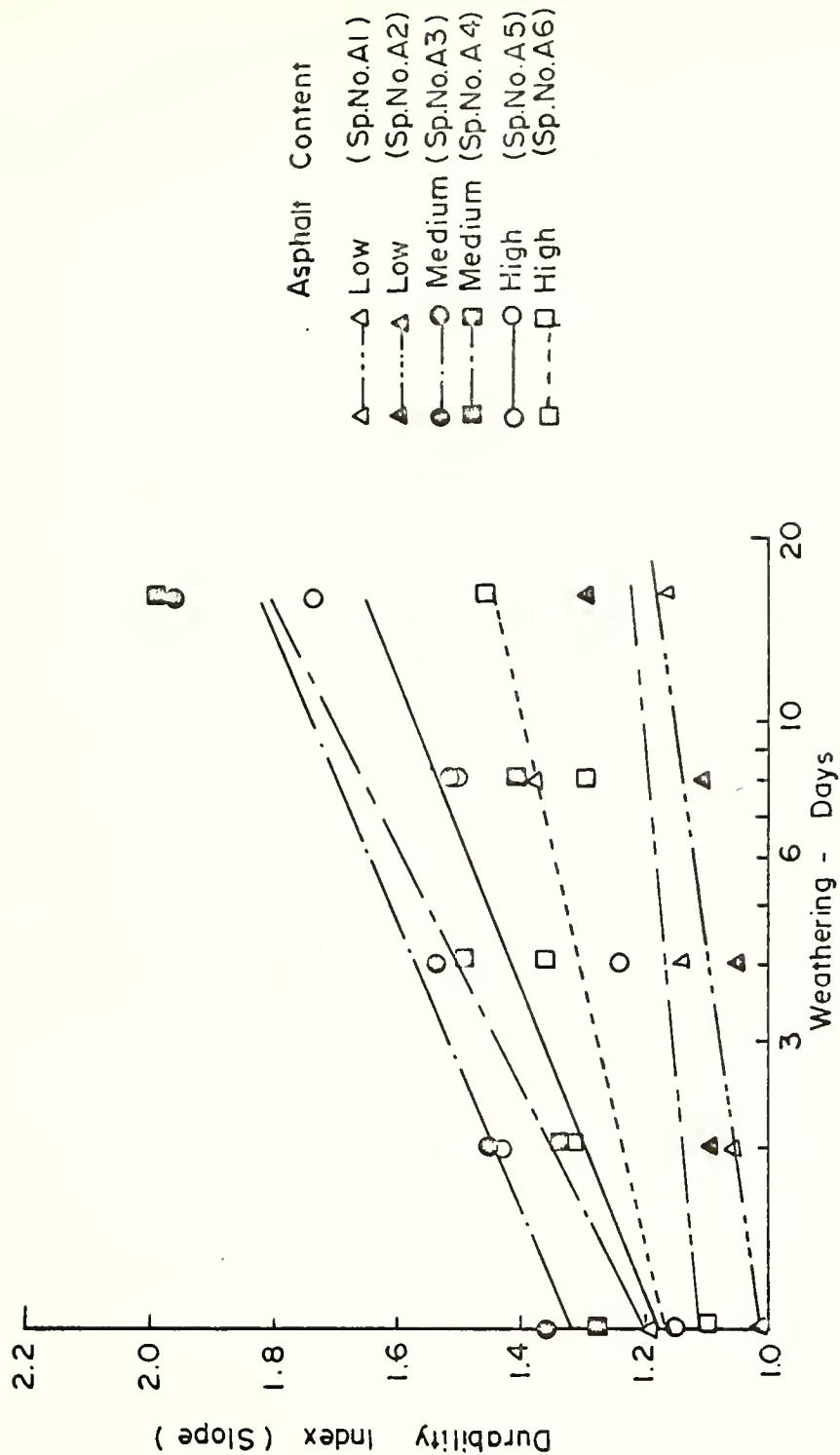


FIGURE 29 - DURABILITY INDEX (SLOPE) VS WEATHERING (OXIDATION) FOR SPECIMENS MADE WITH VARYING ASPHALT CONTENT (GRADED MIXTURE, GROUP A)

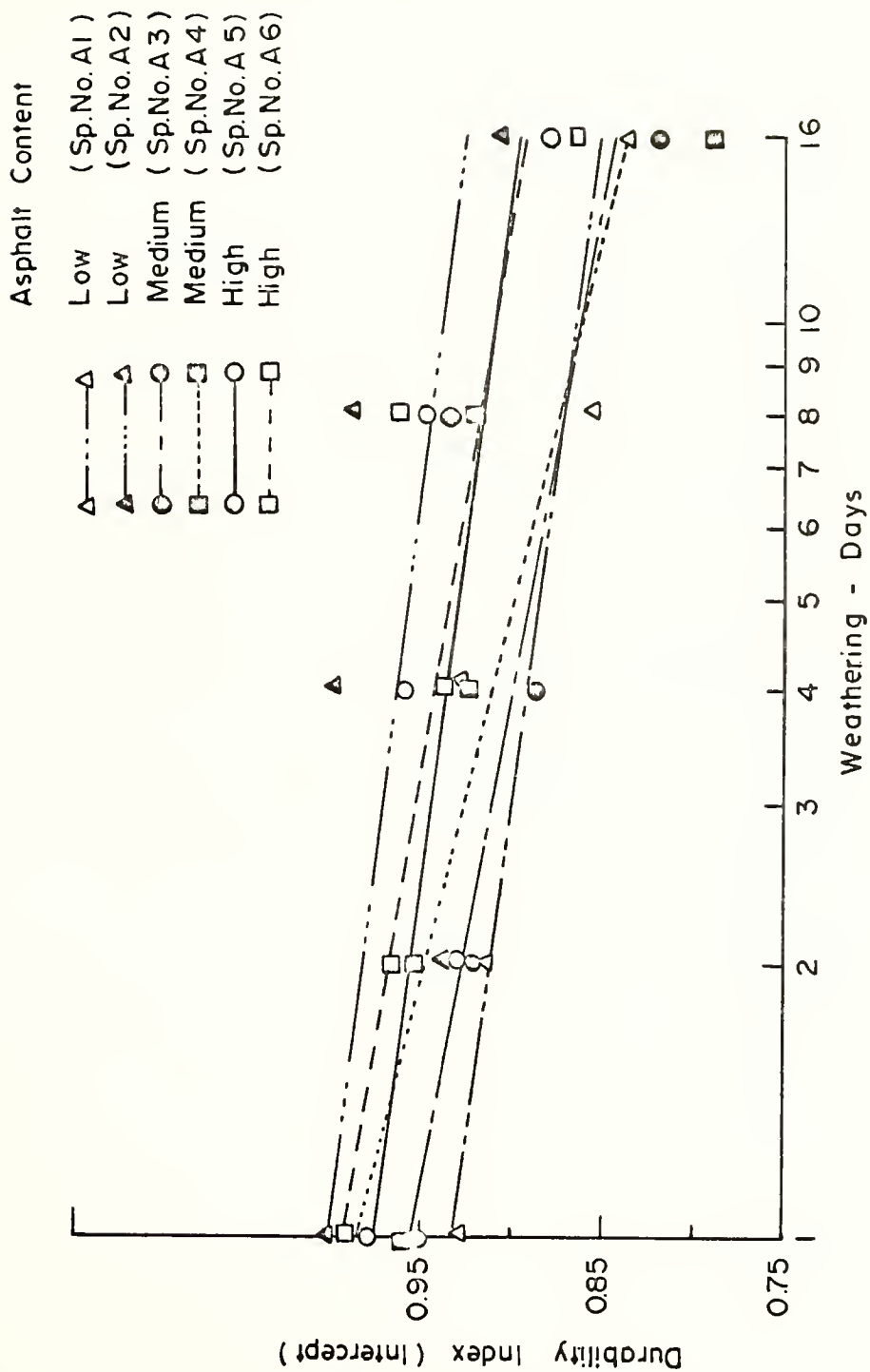


FIGURE 30 - DURABILITY INDEX (INTERCEPT) VS WEATHERING (OXIDATION) FOR SPECIMENS MADE WITH VARYING ASPHALT CONTENT (GRADED MIXTURE, GROUP A)

Table 42. Slopes of the Straight Line Plots Between Durability Index and Weathering (Oxidation) for Specimens with Varying Asphalt Content (Group A)

For Durability Index (Slope)

Asphalt Content								
Low			Medium			High		
Specimen No.	Slope	Ave.	Specimen No.	Slope	Ave.	Specimen No.	Slope	Ave.
A1	.094	.142	A3	.422	.462	A5	.402	.318
A2	.190		A4	.502		A6	.234	

For Durability Index (Intercept)

Asphalt Content								
Low			Medium			High		
Specimen No.	Slope	Ave.	Specimen No.	Slope	Ave.	Specimen No.	Slope	Ave.
A1	-.082	-.062	A3	-.092	-.108	A5	-.067	-.075
A2	-.042		A4	-.124		A6	-.084	

(oxidation). Therefore, if the slope value at no weathering (oxidation) for the above ratio is high, the durability index (slope) will naturally be lower. Thus, the slope of the plot (Figure 28) will also be lower. Similar reasoning can be applied to the durability index (intercept).

In order to examine the extent of initial hardening during mixing, duplicate specimens were prepared (following exactly the same procedure as for Group A) for each of the three levels of asphalt content. The specimens were then kept (under similar conditions) for the same time that had elapsed between the preparation and creep testing at no weathering (oxidation) for specimens in Group A. After the completion of the above time period, asphalt was extracted (ASTM Designation: D 2172) from each of the six specimens and then recovered from the solution using the Abson Method of recovery (ASTM Designation: D 1856). The penetration test (ASTM Designation: D 5) was then carried out on the recovered asphalt. The average penetration value for specimens with 8.0, 5.5 and 3.0 percent asphalt was found to be 189, 187 and 170, respectively. This clearly justifies the hypothesis of excessive asphalt hardening during mixing for specimens with (low) 3.0 percent asphalt content. Based on the above reasoning, the specimens with low (3.0 percent) asphalt content (nos. A1 and A2) were not included in the analysis.

The Analysis of Variance Test was carried out on the durability index (slope) and durability index (intercept) values of the remaining four specimens (nos. A3 to A6), and the results are presented in Tables 43 and 44. The results in both cases (slope and intercept) indicate that there is significant difference between the two levels (medium and

Table 43. Analysis of Variance (ANOVA) and Newman-Keuls Sequential Range Test Results (NKSRT) for Durability Index (Intercept) Values of the Mixtures with Varying Asphalt Content (Group A)

ANOVA

Source	Sum of Squares	Degrees of Freedom	Mean Square	F
Asphalt Content (A)	0.1523	1	0.1523	16.27*
Oxidation-Days (O)	2.7904	4	0.6976	74.53*
Interaction (AxO)	0.3472	4	0.0868	9.27*
Pooled Error	0.0940	10	0.0094	

NKSRT

<u>Asphalt Content</u>		<u>Table of Differences Between Means</u>	
Ranked Order of Means	Ranked Means	Rank	2
1 Medium	1.530	1	0.174*
2 High	1.356		

* Significant at 5 percent level.

Table 44. Analysis of Variance (ANOVA) and Newman-Keuls Sequential Range Test Results (NKSRT) for Durability Index (Intercept) Values of the Mixtures with Varying Asphalt Content (Group A)

<u>ANOVA</u>				
Source	Sum of Squares	Degrees of Freedom	Mean Square	F
Asphalt Content (A)	.006125	1	.006125	20.80*
Oxidation-Days (O)	.042252	4	.010563	35.87*
Interaction (AxO)	.001852	4	.000463	1.57
Pooled Error	.002940	10	.000294	

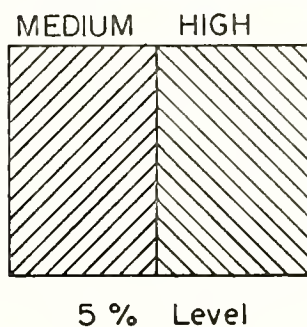
<u>Asphalt Content</u>		<u>Table of Differences Between Means</u>	
Ranked Order of Means	Ranked Means	Rank	2
1 High	0.939	1	0.035*
2 Medium	0.904		

* Significant at 5 percent level.

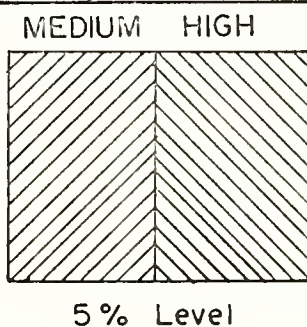
high) of asphalt content. The Newman Keuls Sequential Range Test was now carried out and it was found (Tables 43 and 44) that medium asphalt content level is significantly different to the high asphalt content level at the 5 percent statistical level. This result, presented in Figure 31, establishes the suitability of the test procedure as a measure of asphalt hardening in asphalt mixtures that may be expected due to varying asphalt content.

Based on the above discussion, it is concluded that the accelerated oxidation and creep test procedure can be utilized to predict asphalt mixture behavior from the standpoint of resistance to asphalt hardening due to exposure to air.

For Durability Index (Slope)



For Durability Index (Intercept)



NOTE Difference in values between specimens incorporating different symbols are significant at the specified level

FIGURE 31 - NEWMAN KEULS SEQUENTIAL RANGE TEST RESULTS FOR SPECIMENS MADE WITH VARYING ASPHALT CONTENT (GRADED MIXTURE, GROUP A)

CONCLUSIONS

These conclusions are based on the results obtained in this laboratory study and their discussion as presented. It should be noted that they are applicable to the materials and the testing procedures of this specific research and may not be extended beyond these limits without appropriate verification.

It was concluded that the durability of an asphaltic mixture in terms of its resistance to hardening is directly related to the extent of its exposure to air and that permeability is a direct measure of such exposure. The higher the permeability, the less resistant the mixture is from the standpoint of asphalt hardening. For open (single-size) mixtures, the effect of high permeability can be counteracted by increasing the thickness of the asphalt coating on the aggregate pieces. The conclusions drawn, based on this study, can be enumerated as follows:

1. The ratio of film thickness factor to permeability is the best of those tested for predicting the resistance to hardening of single-size mixtures.
2. The concept of film thickness breaks down in graded mixtures and, of those tested, permeability becomes the best predictor of a mixture's resistance to hardening.
3. The entire void system (total and accessible air voids) is related to permeability in a compacted asphaltic mixture. For

those mixtures tested, there exists a straight-line relationship between the log of permeability and the percent air voids, both total and accessible. However, permeability is most closely related to percent accessible air voids obtained by a hand pumping technique. Since routine permeability measurements in the laboratory may be cumbersome, percent accessible air voids (hand pumping) can be substituted for permeability as a predictor of mixture's resistance to hardening.

4. The creep test results on asphaltic mixture specimens show progressive change with degree of exposure to accelerated oxidation. Also, a comparison between the penetration results of the recovered asphalt from the asphaltic mixtures and their corresponding creep test results indicates that the creep test is a measure of hardening in asphaltic mixtures. Therefore, the creep test can be employed as a non-destructive means for measuring progressive asphalt hardening in asphaltic mixtures.

5. The devised accelerated oxidation and creep test procedure can be employed as a laboratory procedure for the evaluation of asphaltic mixtures from the stand point of resistance to asphalt hardening. After proper correlation with field results, this test can be included as a part of the mixture design procedure for asphaltic mixtures.

SUGGESTIONS FOR FURTHER RESEARCH

The results of this study show that for single-size mixtures the ratio of the film thickness factor to the permeability is the best predictor of a mixture's resistance to asphalt hardening. This information can be applicable to porous friction courses. Because such mixtures have high permeability values, consideration should be given to increasing film thickness as compensation for high permeability as a means of increasing durability. In this way a very porous mixture may still have high resistance to asphalt hardening. When using a straight-run asphalt it may be rather difficult to obtain the thicker asphalt films required. Research efforts should be made in this direction to obtain thicker asphalt films with less tendency to flow. One of the ways it could be done would be to mix filler with asphalt. This modified asphalt should then be used for mixture preparation.

Another possible study could be to correlate laboratory accelerated oxidation to field weathering. Cores could be collected from a newly constructed road, brought to the laboratory and subjected to creep testing. They should then be progressively hardened using the accelerated oxidation technique presented in this study. The creep testing should be carried out on these specimens at regular time intervals. The cores should also be collected from the field at certain time intervals and creep testing be performed on them. The results of

the laboratory hardened and field hardened specimens should then be compared.

In this study the only weathering performed on the asphaltic mixtures was oxidation, and the creep test was performed as a non-destructive test to measure the effect of such weathering. Asphaltic mixtures can be subjected to other weathering cycles such as wetting and drying, freezing and thawing, exposure to moisture etc., and the progressive effect of such weathering cycles could be obtained using the creep test.

Only one penetration grade asphalt and one aggregate type was used in this study. Efforts could be made in the direction of selecting different aggregate-asphalt combinations and subjecting such mixtures to cyclic oxidation and creep testing procedure. The results could be valuable in terms of selecting asphalt-aggregate combinations that will be most durable from the stand point of asphalt hardening.

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BIBLIOGRAPHY

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APPENDIX A

PERMEABILITY MEASUREMENT PROCEDURE

PERMEABILITY MEASUREMENT PROCEDURE

Scope:

This method covers the permeability measurement of asphaltic mixture specimens in the laboratory.

Apparatus:

Mold assembly for the 4 in. (10.16 cm.) diameter specimen (Figures A1, A2 and A3) (suitable modifications should be made for specimens having other sizes), Vacuum Pump, Flowmeters (range for air, 1 - 77,000 ml/min.), Manometer, Pressure Line, Silicone Rubber Sealer (Reference No. 27), Thermometer.

Procedure:

(a) Set the specimen supporter on the base plate. (If the mix is very coarse and has low density so that there is a chance of the mix falling in between the ribs of the specimen supporter (Figure A1), a wire mesh of small openings may be placed on the specimen supporter.) Place the lower collar on the base plate. The lower assembly is now ready to receive the specimen for coating (Figure A4).

(b) Place the specimen on the specimen supporter and coat it with the silicone rubber sealer all around, leaving only about an inch (2.5 cm.) from the top of the specimen (Figure A5). Make sure that enough sealer is applied at the top of the lower collar so that it adheres to the specimen.

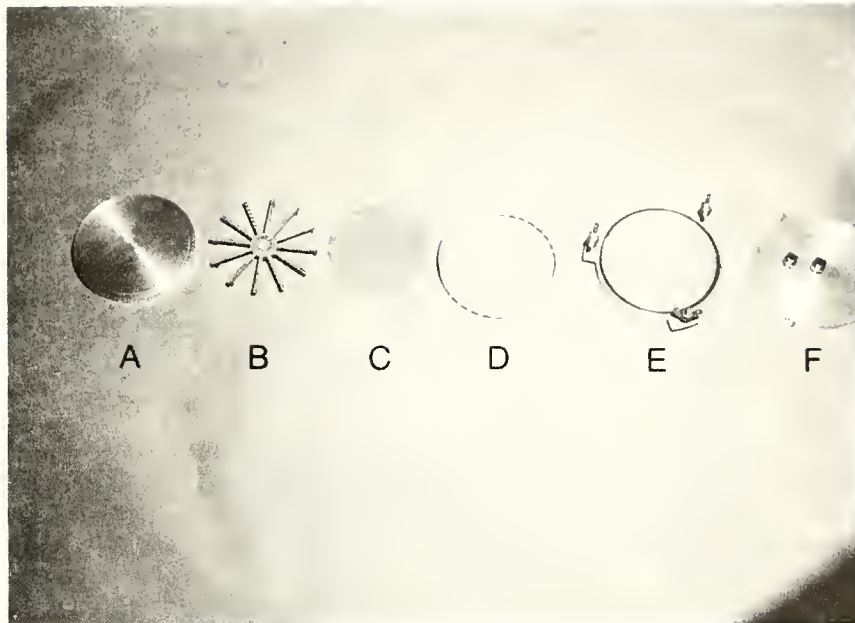


FIGURE A1 - COMPONENT PARTS OF THE MOLD ASSEMBLY

Key to details of Figure A1

- A. Base Plate
- B. Specimen Supporter
- C. Wire Gauze
- D. Lower Collar
- E. Upper Collar with 'O' Ring
- F. Cover Plate

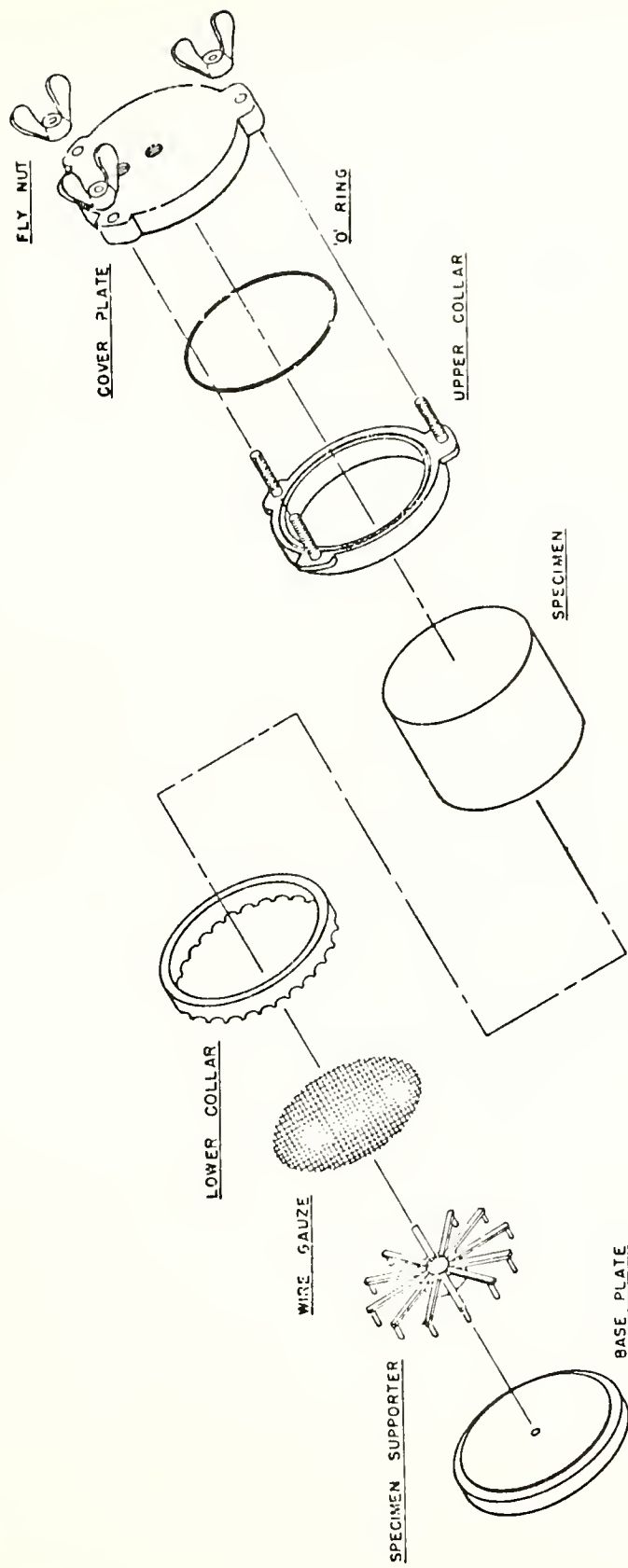


FIGURE A2 - EXPLODED VIEW OF THE MOLD ASSEMBLY

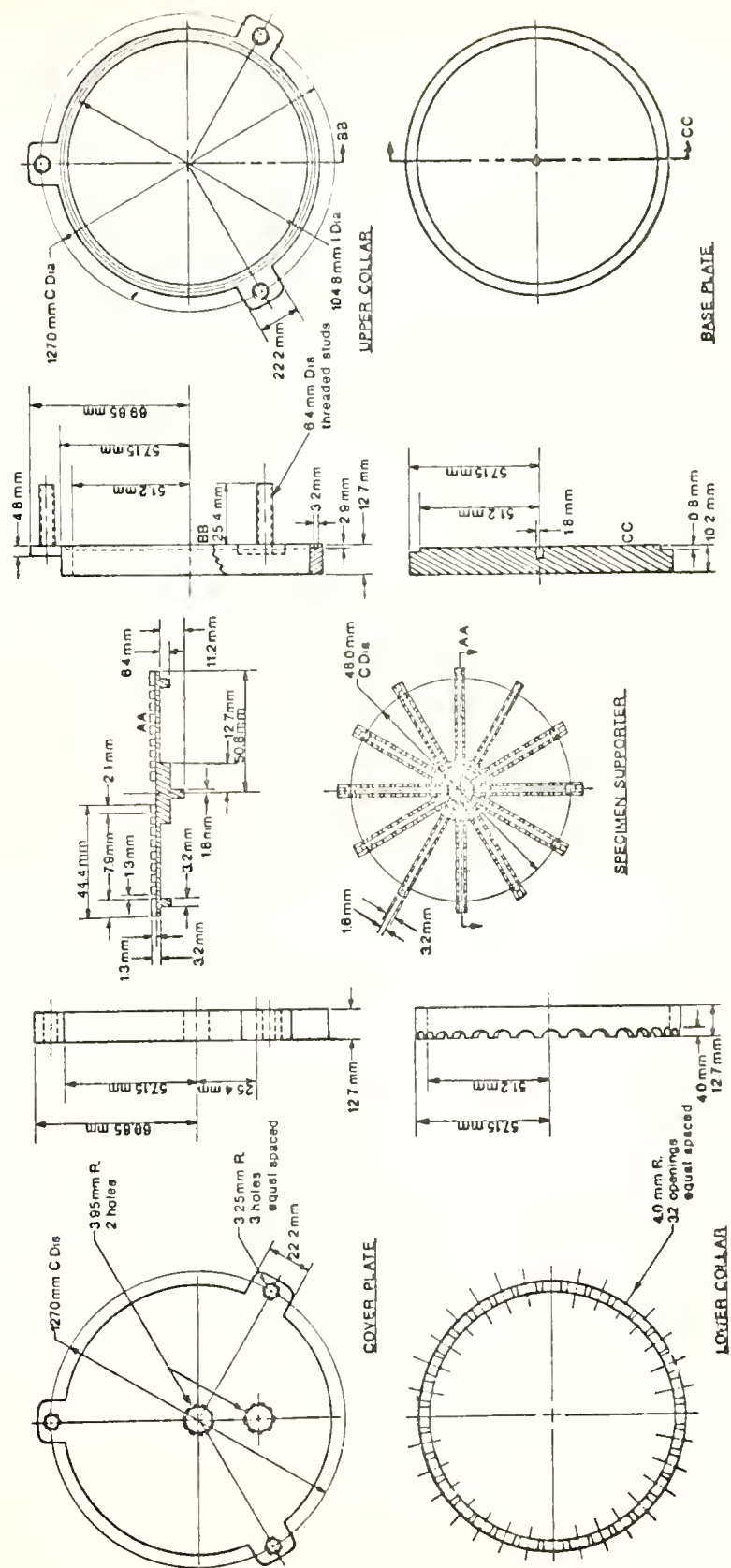


FIGURE A3- DETAIL DRAWING OF THE MOLD ASSEMBLY



FIGURE A4 - LOWER ASSEMBLY READY TO RECEIVE THE SPECIMEN FOR COATING



FIGURE A5 - SPECIMEN COATED TO ABOUT ONE INCH (2.5 CM) FROM THE TOP

(c) After the sealer has partially cured (approximately 8 hours), lift the specimen (the lower collar will be fixed to it), place the upper collar upside down on the base plate, reverse the specimen and seat it on the specimen supporter. The whole assembly should be elevated so that the upper collar sits properly on the base plate. Coat the rest of the specimen with the same sealer, thereby adhering the upper collar to the specimen (Figure A6). Leave the assembly overnight for the sealer to cure.

(d) The next day, turn the specimen upside down, place it on the specimen supporter, seat the cover plate on the upper collar and tighten the flynuts (Figure A7).

(e) Check for leaks. There are two openings in the cover plate: close one and apply pressure gradually through the other opening. Then immerse the entire assembly in water and apply pressure slightly higher than the maximum anticipated suction pressure to be applied during the permeability measurement (Figure A8).

Air will start bubbling through the semicircular holes in the lower collar (Figure A9). Check for any air leaks from the sides of the specimen. If any leak is observed it should be repaired followed by a recheck.

(f) Condition the specimen for creep testing (explained in section, 'Creep Test as a Measure of Asphalt Hardening'). This step can be omitted if the specimen is not to be subjected to creep testing subsequently.

(g) Measure the height of the specimen (H) in inches (Figure A10).

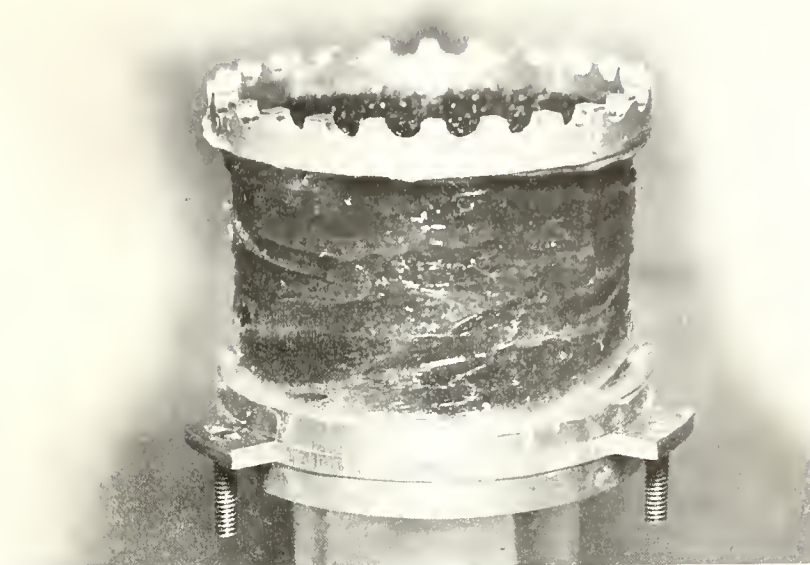


FIGURE A6 - COMPLETELY COATED SPECIMEN



FIGURE A7 - ASSEMBLY READY FOR LEAK CHECK



FIGURE A8 - GENERAL VIEW OF AIR LEAK CHECK SET-UP

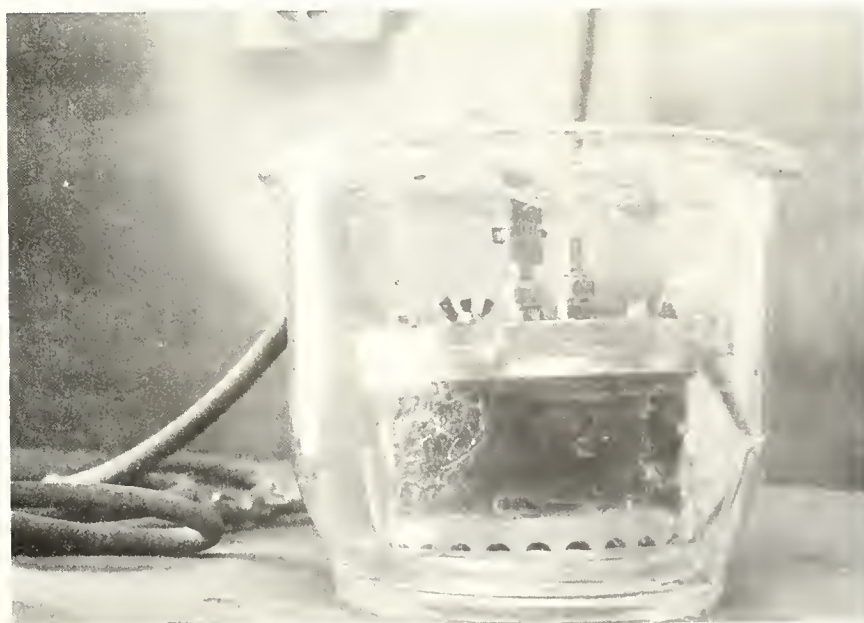


FIGURE A9 - CLOSEUP SHOWING AIR BUBBLING THROUGH THE OPENINGS IN THE LOWER COLLAR

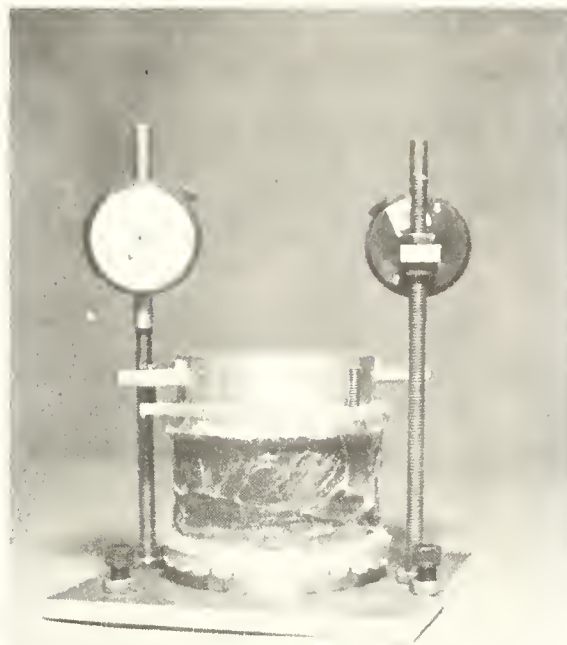


FIGURE A10 - HEIGHT MEASUREMENT OF THE SPECIMEN

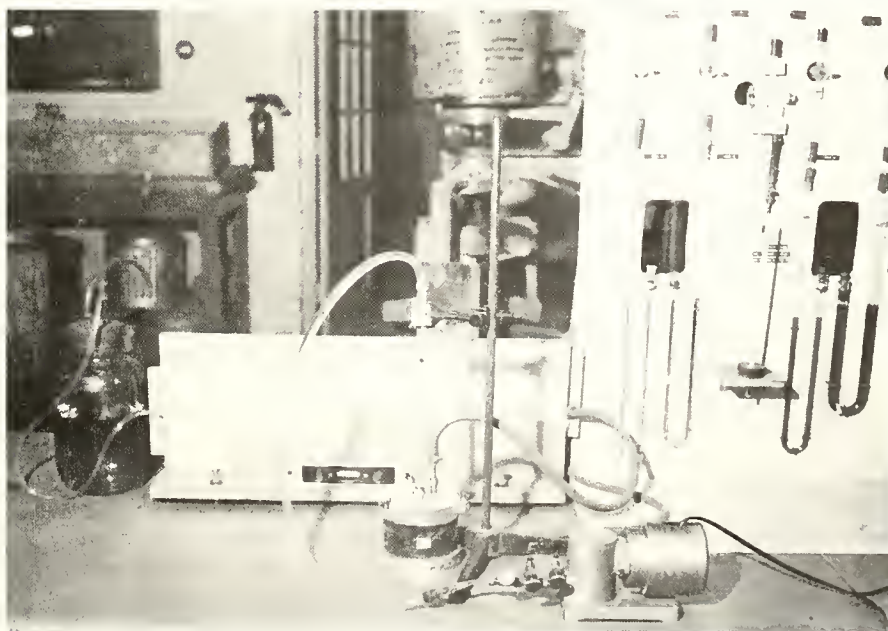


FIGURE A11 - PERMEABILITY MEASUREMENT OF THE SPECIMEN, A GENERAL VIEW

(h) The specimen is now ready for testing. Connect one opening of the coverplate to the flowmeter through which air is to be drawn using a vacuum pump. Connect the other opening to the manometer to record the pressure differential created across the specimen (Figure All).

(i) Using a control valve in the vacuum line, obtain the rate of air flow (R) in ml. per minute through the specimen as shown by the flowmeter at various pressure differential values (ΔP).

(j) Record the test temperature.

(k) Plot the rate of airflow (y-axis) vs pressure difference (x-axis) and obtain the slope (S) of the straight line portion of the curve using a linear regression equation (28).

Calculations:

The conventional formula of permeability as given by Hein and Schmidt (11) is:

$$K = \frac{\mu \bar{Q} L}{A(P_1 - P_2)}$$

where:

K = Permeability, cm. per sec.

μ = Viscosity of air, poises

$\bar{Q}$ = Rate of air flow, cu. cm. per sec.

L = Height of specimen, cm.

A = Cross-sectional area of specimen, sq. cm.

$P_1 - P_2$ = Pressure differential, dynes/sq. cm.

For specimens 4 inches (10.16 cm.) in diameter, a test temperature of 68F(20C), and a value for μ @ 68F(20C) of 1.813×10^{-4} poises (Reference No. 40), the above formula reduces to:

$$K = \frac{3.812 \times 10^{-11} \times R \times H}{\Delta P}$$

where:

R = Rate of airflow, ml. per minute

H = Height of specimen, inches

ΔP = Pressure differential, inches of water

Using the slope of the straight line portion of the curve obtained from the plot of rate of airflow (R) (y-axis) vs pressure difference (ΔP) (x-axis), the formula further reduces to:

$$K = 3.812 \times 10^{-11} \times S \times H$$

where:

K = Permeability, cm. per sec.

S = Slope of the straight line portion of the curve, ml. per min. in.

For temperatures other than 68F(20C), the formula should be suitably modified as follows:

$$K = 3.812 \times 10^{-11} \times S \times H \times \frac{\mu @ \text{ test temperature}}{1.813}$$

NOTE: Appendices B through E, pages 142-241, are not included within this copy of this report. Any reader of this report may secure information about obtaining a copy of an Appendix or Appendices by request to the

Joint Highway Research Project
Civil Engineering Building
Purdue University
West Lafayette, Indiana 47907

The costs for obtaining the Appendices will be nominal and associated with duplication and handling.

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